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METEOROLOGISKA INSTITUTET
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152
CONTRIBUTIONS

ESSAYS IN ENVIRONMENTAL COST-BENEFIT ANALYSIS

VÄINÖ NURMI

FINNISH METEOROLOGICAL INSTITUTE
CONTRIBUTIONS
No. 152

Essays in Environmental Cost-Benefit Analysis

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Doctoral Programme in Economics
Faculty of Agriculture and Forestry
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Helsinki, Finland

ACADEMIC DISSERTATION in Environmental Economics

To be presented, with the permission of the Faculty of Agriculture and Forestry of the University of Helsinki, for public criticism in auditorium (Room 110, LS B1), (Latokartanonkaari 7, Viikki Campus, Helsinki) on 17 May 2019, at 12 noon.

Finnish Meteorological Institute
Helsinki, 2019

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ISBN 978-952-336-075-4 (paperback)
ISBN 978-952-336-076-1 (pdf)
ISSN 0782-6117
Erweko
Helsinki 2019

ACKNOWLEDGEMENTS

I would like to take the opportunity to thank those people and institutions that have made it possible for me to write this thesis. Research is always a team effort and I have always been fortunate enough to have an excellent team to work with.

First of all, I want to thank Professor Adriaan Perrels for giving me an opportunity to start a career as a researcher at the Finnish Meteorological Institute (FMI). His support was invaluable, particularly during my early years at the Institute. I still value our discussions very highly and his support was very important when writing the articles. As I have been very lucky to have had two active supervisors, I would also like to thank Professor Markku Ollikainen, who helped me a great deal in writing the last part of my thesis, the introduction. It was a very smooth process thanks to his insightful comments. Thanks are also due to Heikki Tuomenvirta at FMI for being a supportive boss and for giving me the luxury of being able to focus on my thesis by arranging the necessary resources and time.

Of course, I also want to thank all my co-authors. Articles II and III of the thesis were written for the most part with Karoliina Pilli-Sihvola. By "with" I mean that we shared the same screen and did both the analyses and writing at that screen. I have always appreciated working with Karoliina, and I think we make a great team and complement each other as researchers. In the case of Article IV, Athanasios Votsis provided his expertise in modelling the housing market interactions, which improved the article immensely. Article I was written with Heini Ahtiainen, and without her expertise I doubt it would ever have been published in such a good journal – or published at all. Special mention goes to Richard Foley for making the language of the thesis as close to English as possible. Without the final comments of Reija Ruuhela and Sanna Luhtala in the editing process, this thesis would not have been printed in time.

I would also like to thank Riina Haavisto, Atte Harjanne, Chiara Lombardini, Marko Lindroos, Sampo Pihlainen and all other team members at FMI and the University of Helsinki for valuable discussions and comments regarding my research and my thesis.

Thanks are in order to the pre-examiners, Professors Jukka Pirttilä and Artti Juutinen, for their very thorough and supportive statement on my thesis. I am also grateful to Professor Wouter Botzen, who has agreed to be my opponent in the public examination of the thesis. My deepest gratitude also goes to the Maj and Tor Nessling Foundation for the financial support that enabled me to focus on my studies and write the articles.

Education has always been one of the things my family has valued most, even more than wealth. Thank you, Päivi and Rauno, my loving parents, for always supporting me and furthening opportunities for me to pursue my dreams. I would also like to thank my wife, Eeva-Reetta, for believing in me and for staying with me despite my poor financial decisions (i.e., doing research) and for having to do more housework than I did during the busiest times writing this thesis. Lastly, I would like to thank Saga and Remus for forcing me to take breaks from research and for being my inspiration.

Helsinki, May 2019

Väinö Nurmi

Published by	Finnish Meteorological Institute (Erik Palménin aukio 1), P.O. Box 503 FIN-00101 Helsinki, Finland	Series title, number and report code of publication Finnish Meteorological Institute Contributions 152, FMI-CONT 152 Date May 2019
Author	Väinö Nurmi	
Title	Essays in Environmental Cost-Benefit Analysis	

Abstract

This thesis applies cost-benefit analysis (CBA) to certain environmental questions and through its results contributes to both the theoretical literature on CBA in environmental economics and practical issues in the application of CBA to environmental problems. The work comprises an introduction and four articles, which address three common thematic areas: 1) distributional issues, 2) climate change adaptation, and 3) urban ecosystem services.

Article I contributes to the literature through analyses that i) provide a connection between the income effect and distributional issues; ii) compare weighting schemes both theoretically and empirically; iii) show how weights could be incorporated into a CBA in practice; and iv) demonstrate that results are sensitive not only to whether weights are applied, but also to the choice of the inequality parameter and spatial resolution.

Article II analyzes whether over-investment in disaster risk reduction and climate change adaptation is a legitimate economic concern and examines how the public reacts to major infrastructure investments. The results constitute a contribution to both the theoretical and empirical literature on the economics of climate change adaptation.

Article III evaluates how potential innovations in weather services can reduce weather sensitivity and, consequently, decrease the negative effects of climate change on transport, particularly in the road transport sector. The article illustrates how innovations in the provision and use of weather and climate information can be beneficial for adapting to the changing climate and contributes to the empirical literature on the economics of climate change adaptation.

Article IV presents a CBA of a relatively novel feature in the urban green portfolio: green roofs. The specific objectives of the research are i) to facilitate benefit-transfer of ecosystem services from one urban area to another by providing detailed information on valuation methods and the role of different assumptions and parameter values and ii) to include scenic values as a benefit item based on a formal and trackable analysis rather than on a guess. The article contributes to the empirical literature related to both the cost-benefit analysis of urban ecosystem services and the economics of climate change adaptation.

Publishing unit	Finnish Meteorological Institute, Weather and Climate Change Impact Research	
Classification (UDC) 33 Economics, Economic science 364.682 Environmental welfare problems		Keywords cost-benefit analysis, distributional weights, climate change, adaptation to climate change, ecosystem services, valuation
ISSN and series title 0782-6117 Finnish Meteorological Institute Contributions		
ISBN 978-952-336-075-4 (paperback); 978-952-336-076-1 (pdf)	Language English	Pages 51

ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

Julkaisija	Ilmatieteen laitos, (Erik Palménin aukio 1) PL 503, 00101 Helsinki	Julkaisun sarja, numero ja raporttikoodi Finnish Meteorological Insititute Contributions 152, FMI-CONT 152 Julkaisuaika Toukokuu 2019

Tekijä Väinö Nurmi

Nimeke Tutkimuksia kustannushyötyanalyysin soveltamisesta ympäristötaloustieteessä

Tiivistelmä

Tässä tutkielmassa sovelletaan kustannushyötyanalyysiä (KHA) ympäristöön liittyviin kysymyksiin. Tulokset vievät eteenpäin sekä KHA-analyysin teoreettista kirjallisuutta että käytännön sovellettavuutta ympäristökysymyksiin. Työ koostuu neljästä artikkelista, joissa on kolme poikkileikkaavaa teemaa: 1) tulojakauma-kysymykset, 2) ilmastonmuutokseen sopeutuminen ja 3) urbaanit ekosysteemipalvelut.

Artikkeli I pääkontribuutio kirjallisuuteen on i) luoda yhteys tulovaikutuksen ja tulojakauma-kysymyksen välille, ii) vertailla eri painotustapoja teoreettisesti ja empiirisesti, iii) osoittaa, miten painotukset voidaan käytännössä sisällyttää KHA:n, iv) näyttää tulosten herkkyys paitsi siihen, painotetaanko hyötyjä vai ei, myös siihen, mikä painotustapa valitaan ja mitä maantieteellistä tarkkuutta käytetään.

Artikkeli II analysoi esimerkin avulla, onko liiallinen panostaminen ilmastonmuutokseen sopeutumiseen ja onnettomuusriskien vähentämiseen todellinen huolenaihe. Liiallinen panostus määritellään taloudellisen tehokkuuden avulla. Tulokset myötävaikuttavat ilmastonmuutokseen liittyvän taloustieteen teoreettiseen ja käytännön kirjallisuuteen.

Artikkelissa III arvioimme, miten sääpalveluihin liittyvät innovaatiot voivat vähentää yhteiskunnan sääherkkyyttä ja vähentää ilmastonmuutoksen tuomia negatiivisia vaikutuksia tieliikenteelle. Artikkelissa näytetään, miten sääpalveluiden jakeluun ja käytettävyyteen liittyvät innovaatiot ovat hyödyllisiä ilmastonmuutokseen sopeutumiselle. Tulokset myötävaikuttavat ilmastonmuutokseen liittyvän taloustieteen käytännön kirjallisuuteen.

Artikkeli IV käsittelee viherkattojen kustannushyötyanalyysiä. Tämän tutkimuksen päätavoitteet ovat: i) mahdollistaa tulosten siirtäminen toiselta urbaanilta alueelta toiselle antamalla mahdollisimman tarkat tiedot tutkimuksessa käytetyistä menetelmistä ja parametreista, ii) sisällyttää viherkattojen maisemahyödyt yhtenä hyötylajina mukaan. Tulokset myötävaikuttavat sekä ekosysteemipalveluihin liittyvän KHA:n käytännön kirjallisuuteen että ilmastonmuutokseen liittyvän taloustieteen käytännön kirjallisuuteen.

Julkaisijayksikkö Ilmatieteen laitos, Sään ja ilmastonmuutoksen vaikutustutkimus

Luokitus (UDK) 33 364.682	Asiasanat kustannushyötyanalyysi, tulojakaumapainotukset, ilmastonmuutos, ilmastonmuutokseen sopeutuminen, ekosysteemipalvelut

ISSN ja avainnimike
0782-6117 Finnish Meteorological Institute Contributions

ISBN 978-952-336-075-4 (nid); 978-952-336-076-1 (pdf)	Kieli englanti	Sivumäärä 51

LIST OF ORIGINAL PUBLICATIONS

I. Nurmi, Väinö; Ahtiainen, Heini. 2018. Distributional Weights in Environmental Valuation and Cost-Benefit Analysis: Theory and Practice. Ecological Economics, 150, 217–228.

II. Nurmi, Väinö; Pilli-Sihvola, Karoliina; Perrels, Adriaan; Gregow, Hilppa. 2019. Overadaptation to climate change? The case of the Finnish Electricity Market Act 2013. Submitted to Economics of Climate Change and Disasters (2019), 1–30.

III. Pilli-Sihvola, Karoliina; Nurmi, Väinö; Perrels, Adriaan; Harjanne, Atte; Bösch, Patrick; Ciari, Francesco. 2016. lnnovations in weather services as a crucial building block for climate change adaptation in road transport. European Journal of Transport & lnfrastructure Research, 16, 150–173.

IV. Nurmi, Väinö; Votsis, Athanasios; Perrels, Adriaan; Lehvävirta, Susanna. 2016. Green Roof Cost-Benefit Analysis: Special Emphasis on Scenic Benefits. Journal of Benefit-Cost Analysis, 7, 488–522.

This thesis consists of four articles. Väinö Nurmi is the lead author in articles I, II and IV. ln all of the articles, he has been the main contributor to the economic analysis. ln articles I, II and IV he has also been the main contributor to the theoretical aspects of the articles. Väinö Nurmi has come up with the research idea and acquired the funding for articles I and IV; articles II and III have been written as parts of research projects called TopDad (funded by European Commission) and Elastinen (Finnish Government Research program). Väinö Nurmi had the main responsibility of writing the articles I, and IV and shared the main responsibility of writing articles II and III.

Table of Contents

1 INTRODUCTION

This thesis applies cost-benefit analysis (CBA) to certain environmental questions and through its results contributes to both the theoretical literature on CBA in environmental economics and practical issues in the application of CBA to environmental problems. More specifically, the work addresses the following thematic areas: 1) distributional issues, 2) climate change adaptation, and 3) urban ecosystem services.

1.1 Cost-benefit analysis in environmental economics

CBA is a rule, tool (e.g., Boadway, 2006) or element in the social decision-making process (Arrow, 1996; Nyborg, 2014). It compares the benefits of a project or a policy to its costs; benefits are defined as the increases in individuals' wellbeing, and costs as decreases in that wellbeing. (e.g., Boardman, 2006; Boadway, 2006). The changes in wellbeing are usually expressed as equivalent changes in income and are aggregated over individuals (e.g., Johansson, 1993). If the changes in wellbeing occur at different points in time, they are all converted into present value using a chosen discount factor or factors (e.g., Arrow et al. 2013). With this procedure, the net present value of benefits, that is, benefits minus costs, can be compared between projects.

The classical interpretation of CBA is that it constitutes a social decision rule whereby projects are ranked based on the net benefit criterion and the most efficient project should be chosen on this basis (e.g., Freeman, 2014; Atkinson & Mourato, 2006; OECD, 2018). However, there are several drawbacks to this procedure, such as insensitivity to distributional aspects and difficulties in determining a monetary value for some impacts. Due to these shortcomings, cost-benefit analysis can also be seen as no more than one piece of information by which projects may be ranked. (Arrow et al. 1996; Nyborg, 2014).

The theoretical foundation of CBA, still applied today, was established in the 1940s, most notably by the economists Hicks (1941, 1942, and 1943), Kaldor (1939) and Scitovsky (1941). The method itself dates back to the nineteenth century and the work of French engineer and economist Jules Dupuit (1944, 1853), who not only put forward the idea of comparing the marginal benefits and costs of a project, but also expressed his view on how these should be measured (e.g., Pearce, 1998; Atkinson & Mourato, 2006; Quah & Haldane, 2007). The first official regulation related to CBA dates back to 1936, when the Flood Control Act in the United States prescribed that water-related projects should proceed only if the benefits exceed the costs (e.g., Pearce, 1998; Quah & Haldane, 2007). The Act prompted various government agencies to develop their own elementary guidelines on the application of CBA, but typically these only served to justify their own projects. The need for formal guidelines was first met in the 1950, when the Green Book – officially named *Proposed Practices for Economic Analysis for River Basin Projects* – was published. (Pearce, 1998; Quah & Haldane, 2007).

In the early guidelines, environmental externalities were, if anything, a minor detail. It was not until the 1970s that they had become such an evident by-product of production and transportation that they could no longer be ignored in economic analyses. Research programs financed by the Environmental Protection Agency (EPA) of the United States in that same decade yielded the first methods for valuating natural assets. (e.g., Pearce, 1998). In the course of the decade the theoretical concepts were generalized to account for welfare effects of changes in environmental quality (e.g., Mäler, 1974; Randall & Stoll, 1980).

The optimal treatment of externalities is still one of the central themes of environmental economics today. Deriving the conditions for optimal mechanisms requires a knowledge of the benefits and costs of the relevant externalities. If the impacts of an externality can be reduced, the benefits and costs of the reduction should be included in any analysis. In addition to having to deal with externalities, many environmental problems involve the optimal provision of services from natural ecosystems, or *ecosystem services*. Determining optimal provision also requires knowledge of the benefits and costs of the services.

Given the nature of the issues dealt with in environmental economics, CBA is one of the main tools for policy and project evaluation and underpins economic analysis of environmental assets (Freeman et al. 2014). However, as mentioned, the method has shortcomings that hamper its straightforward application as a social decision rule. Both theoretical (e.g., Boadway, 1974; Scitovsky 1941; Blackorby & Donaldson, 1990) and ethical problems (e.g., Mishan, 1982; Sen, 1990; Dreze, 1998; Nyborg, 2014) have been identified in using CBA as a decision rule. Arguably the most fundamental problem in standard CBA is the treatment of distributional aspects – both within and between generations (Nyborg, 2014; Blackorby & Donaldson, 1990). If monetary welfare changes are not adjusted or "weighted" to take into account the social (decreasing) marginal utility of money, CBA systematically favors those who value money the least relative to alternative numeraires (Brekke, 1997; Dreze, 1998; Boadway, 2006).

Article I of the thesis focuses on distributional issues and presents the use of distributional weights in an environmental CBA. Distributional weights are a theoretically sound way to deal with distributional issues. As listed in Smith et al. (2017), along with insensitivity to distributional issues, many other reasons can be found to criticize the use of CBA: imperfect valuation methods, sensitivity to assumptions regarding intergenerational preferences (e.g., discount rate), a tendency to favor monetized (often tangible market) costs and benefits, and inconsistent and often inadequate treatment of non-quantifiable (often intangible non-market) costs and benefits (Atkinson and Mourato 2008; Boardman et al. 2006; Bonzanigo and Kalra 2014; Florio 2014). Rather than being absolute barriers to using CBA, these are issues that should be addressed carefully in each application. In each of the applications taken up in this thesis, the problems have been solved in the particular context of the application. The difficulty of determining hard-to-quantify benefits, such as information and aesthetic benefits, is one of the main themes in both Articles III and IV.

1.2 Policy relevance of CBA in environmental issues

Examples of environmental externalities are numerous: climate change caused by greenhouse gases (GHG), air pollution caused by emissions such as small particles, or water quality issues caused by eutrophication. Two main types of mechanisms to deal with these externalities have been developed in environmental economics: 1) Pigouvian taxes (or subsidies) and 2) tradable pollution permits. (e.g., Hanley et al. 1997). Both of these solutions can, in theory, restore the Pareto-efficient outcome. Both require comparison of benefits and costs, thus making a case for CBA. For example, in CBAs dealing with climate change, the cost of the externality is often referred to as the social cost of carbon (SCC) (e.g., Nordhaus, 2017; Tol, 2018), and the benefits are the social benefits that people accrue from the consumption enabled by cheap energy or from other forms of production that cause greenhouse gases. However, the modelling of SCC is an extreme case of CBA that requires multiple integrated modelling tools (e.g., Nordhaus, 2017).

Economic agents and societies may mitigate externalities or undertake measures to reduce the costs that external effects cause: economic agents can reduce an individual's exposure to air pollution (Laumbach et al. 2015), use technological solutions to purify dirty drinking water (e.g., Shannon et al. 2010) or adapt to changing weather conditions (e.g., IPCC, 2014a). In theory, the possibility to reduce the negative impacts of external effects should be considered when choosing the optimal level of taxation or pollution permits. At the social optimum, the marginal cost of reducing a particular externality, the marginal costs of reducing the costs of the externality, and the marginal benefit of the production or consumption causing the externality should all be equal. (Pearson, 2011; Tol et al. 2005).

In the case of climate change, a thorough analysis would require a global CBA of sorts taking adaptation, mitigation and residual climate change impacts into account. However, in practice, an analysis of this scope is very rarely feasible. For example, adaptation and mitigation decisions are made by different people operating at different spatial and temporal scales, which makes it nearly impossible to analyze the trade-offs between the two processes (Tol et al. 2005). As adaptation usually takes place at the individual, local, regional or national scale, global mitigation efforts are usually excluded from the analysis: climate change is taken as a given and the related uncertainty is dealt with using climate change scenarios, such as representative concentration pathways (RCPs) (e.g., Nassopoulos et al. 2012). In a local - rather than global - context, CBA is the main tool for assessing and ranking adaptation policies and measures (e.g., IPCC, 2014b). However, views have been put forward criticizing the use of CBA for such purposes (e.g., Smith et al., 2017).

As the example of adaptation would suggest, CBA is a commonly used tool for policy and project analysis throughout the world. Guidelines to promote the use of CBA have been published by the EU (EU, 2014), OECD (2018), EPA (2010) and the UN (2016), among other organizations. CBA is linked to environmental policy also by regulation. In the U.S., regulators of environmental policy, such as the EPA, have an obligation to file a

Regulatory Impact Analysis, which includes a CBA. (e.g., Arrow et al. 1996). In the EU, Articles 100 and 102 of Regulation 1303/2013, which applies to major projects, explicitly state that a CBA needs to be carried out if the total costs of the project exceed 50 million euros (EU, 2014). In addition, many sectoral EU policies, such as REACH (EC 1907/2006), which aims to "improve the protection of human health and the environment through the better and earlier identification of the intrinsic properties of chemical substances", require that restriction proposals include a CBA. In practice, this means that when a chemical substance is either restricted or approved, a CBA is part of the decision base. As of February 2018, applications for 196 different uses for a total of 24 substances had been submitted to the European Chemical Agency (ECHA). Based on the experience of ECHA, most applicants had more or less thoroughly evaluated the benefits and costs, albeit with some tendency to overstate the positive welfare implications. After the scientific officers of ECHA had reviewed the applications, the European Commission decided to follow their advice (Georgiou et al. 2018). This is a good example of how regulation supports the use of CBA, which in turn has a direct effect on policy.

Regulation can thus directly require policy makers to perform a CBA of a given policy measure. Applying CBA in decision making is, however, a more complex undertaking than looking at different regulatory frameworks: in the case of environmental issues, for instance, decisions are taken at many different stages and policy levels and at each stage and level there are multiple agents using different sets of information as the basis of their decisions. In Article II of the thesis, we examine this complexity through a look at Finnish legislation regulating the energy markets. In an illuminating example from the UK, Atkinson et al. (2018) note that the Department for Environment, Food and Rural Affairs (Defra) is the government department with responsibility for environmental policy, but, given that environmental impacts result from decisions taken in other policy areas, many other government departments are relevant as well, one being the Department for Transport and Department of Business, Energy and Industrial Strategy. Other public bodies, such as the Environment Agency or the Forestry Commission, also have responsibilities for implementing environmental policy. Continuing the list, bodies that regulate private firms play a role here as well, as do the firms themselves. On top of all these actors, one may find EU-level policies or international laws that restrict and guide national-level decision making. Given the complexity of regulatory decision making, policy processes fall outside the scope of the thesis.

Notwithstanding, it will be illuminating to point out some trends in the use of environmental valuation and CBA in environmental policies. First, it is clear (e.g., Atkinson, 2018; Adelle et al. 2012) that CBA is increasingly used in making environmental decisions, but it is almost always as a part of the information base rather than a social decision rule. Second, one rarely sees an explicit explanation of how CBA affects the final decision. One of the aims of Article I, which focuses on distributional weights, was to add to the transparency of decision making by allowing practitioners of CBA to explicitly state distributional effects in quantitative terms rather than merely listing them qualitatively. The elaboration of such systematic procedures, as well as ones in other areas where CBA is often found to be lacking (such as valuation of intangible assets, a topic taken up in Article IV), may enable more explicit use of CBA in policy decisions.

It should be noted that CBA is not the only decision rule or tool that policy-makers can use to assess the impacts of a policy or project. Nyborg (2014) calls for Cost-Impact Analysis, in which impacts are expressed in physical units but costs in monetary terms. The closely related Multi-Criteria Analysis is a tool in which decision-makers first state the criteria by which a policy is evaluated and the impacts are then evaluated based on each criterion. Criteria can also be ranked. (Baltussen & Nielsen, 2006). Cost-Effectiveness Analysis ranks different policies based on a cost-effectiveness ratio, which is calculated as the ratio of costs to a single, quantifiable impact. Of the different options, CBA is thus the only one that quantifies both benefits and costs in terms of the same units. While having the weakness of ignoring distributional impacts, CBA makes it possible to eliminate the difficulty of ranking competing criteria and the subjective evaluation of their importance when interpreting the results. Article I puts forward the argument that if distributional aspects are explicitly included in a CBA, the results will have greater weight in making the policy decision; with the inclusion of distributional concerns, the analysis is also more justified from the theoretical and ethical point of view.

1.3 Objectives of the thesis

This thesis contributes to the use of CBA in the economic analysis of environmental issues. It consists of four articles, which address several common thematic areas with three cross-cutting objectives:

The first objective is to discuss how distributional issues have been taken into account in environmental policy, review the salient theoretical issues and illustrate how distributional issues can be handled in practice. Distributional issues are the focus of Article I.

The second objective, pursued in Articles II, III and IV, is to contribute to the growing literature on economic analysis of climate change adaptation measures and policies.

The third objective, the focus of Article IV, is to identify and valuate the welfare-improving effects of urban ecosystem services.

More specifically, Article I makes the following contributions to the literature: It i) provides a connection between the income effect and distributional issues; ii) It compares weighting schemes compared both theoretically and empirically; iii) shows how the weights could be incorporated in a CBA in practice; and iv) demonstrates that results are sensitive not only to whether the weights are applied, but also to the choice of the inequality parameter and spatial resolution.

Article II analyzes whether over-investment in disaster risk reduction and climate change adaptation is a legitimate economic concern and how the public reacts to major infrastructure investments, the costs of which they ultimately bear. In the article, we undertake an *in media res* (in the midst of things) CBA of the amended Finnish Electricity Market Act of 2013 (588/2013). As a sizable investment project for disaster risk reduction and climate change adaptation with quantifiable benefits, costs and uncertainty, the Act serves as a good case for the use of a cost-benefit analysis to assess the efficacy of disaster risk reduction and climate change adaptation measures from an economic perspective.

Article III evaluates how potential innovations in weather services can reduce weather sensitivity and, consequently, decrease the negative effects of climate change on transport, particularly in the road transport sector. The study focuses on road transport for two reasons. First, it is the mode of transport most vulnerable to extreme weather, at least if assessed in terms of the aggregate costs related to extreme weather events (Nokkala et al., 2012). In Europe, approximately 10 percent of road accidents can be attributed to extreme weather events (Nurmi et al., 2012), a rate which translates into more than 20 billion euros per year (Nokkala et al., 2012). Second, it serves as a good example to illustrate how innovations in the provision and use of weather and climate information can be beneficial for adapting to the changing climate. In this way, it shows how such information, which has features of a public good, can be evaluated in economic terms.

In Article IV, we perform a CBA on a relatively novel feature in the urban green portfolio, green roofs. Green roofs are roofs that are partially or (almost) completely covered by vegetation – through planning, not neglect. Green roofs are an increasingly common feature of cities' urban planning toolset. Local adaptation plans around the world list green roofs as a tool for both storm-water management and attenuation of the urban heat-island effect, with the cities adopting such plans including Vancouver, Copenhagen, London, Melbourne, Singapore, Chicago, and Barcelona. In addressing this topic, Article IV can be seen as furthering both the second and the third objective of the thesis. The more specific objectives of the article are i) to facilitate benefit-transfer of ecosystem services from one area to another by providing detailed information on valuation methods and the role of different assumptions and parameter values and ii) to include scenic values as a benefit item in the study based on a formal and trackable analysis rather than on a guess.

2 THEMATIC AREAS OF THE THESIS

There are three main thematic areas that the CBA applications in this thesis: distributional issues, climate change adaptation, and ecosystem services. These themes are interconnected: distributional issues are very important in both adaptation policy analysis and deciding on the provision of ecosystem services. Ecosystem services play an increasingly acknowledged role in climate change adaptation, for example, in reducing the discomfort of heat waves in urban areas or reducing the need for cooling energy. The sections that follow take up the thematic areas in more detail.

2.1 Distributional issues

CBA is built on the Kaldor-Hicks efficiency criterion (e.g., Boadway, 2006; Coleman, 1980; Adler and Posner, 1999), which allows a favorable project to have both winners and losers; the winners compensate the losers but still end up being better off. If compensation is paid, the project turns out to be a Pareto Improvement, but no actual compensation is required for Kaldor-Hicks efficiency (Coleman, 1980). The absence of compensation in the latter has sparked serious criticism, for it disregards distributional consequences (e.g., Mas Colell et al. 1995, pp. 831; Boadway, 2006; Dreze, 1998; Brekke 1997) and is not democratic in the sense that individuals who value money the least (i.e., the rich) have the highest standing in such a the analysis. Formally, this can be proven by studying the symmetry properties of the decision rule, as is done in Article I. These issues are perhaps most simply illustrated in Nyborg (2014), which serves as an introduction to the topic:

An individual's utility U_i is written as a function of his or her income y_i and the level of environmental good q:

$$U_i = u_i(y_i, q) \qquad [1]$$

Next, consider a marginal change following a public project; the change in utility is then:

$$dU_i = u_{iy}dy + u_{iq}\, dq \qquad [2]$$

In basic terms, willingness-to-pay (WTP) is the maximum amount of income y an individual is willing to give up in order to gain a higher quantity or quality of environmental good q. By setting the change in utility to zero and using equation [2], the – dy, or WTP for a marginal change in q, can be written as:

$$WTP = \left(\frac{u_{iq}}{u_{iY}}\right) dq \qquad [3]$$

The WTP in equation [3] can also be interpreted as a proxy for the actual WTP for a non-marginal change in q, assigned the value q_0. Next, assume that there is a cost for the project, of which an individual i must pay C_i. Setting $dy = -C_i$ and using equations [2] and [3], we obtain:

$$dU_i = u_{iy}(WTP - C_i) \quad [4]$$

Next, assume a social welfare function (SWF) that can be expressed as:

$$W = w(u_1, \dots, u_n) \quad [5]$$

Now, the project's impact in the margin on social welfare can now be written as:

$$dW = \sum_i w_i' \, u_{iy}(WTP_i - C_i) \quad [6]$$

This is very close to the aggregation rule in a standard CBA, with the exception that in a standard CBA, $w_i' u_{iy}$=1 holds for all individuals or, rearranging,

$$w_i' = \frac{1}{u_{iy}} \quad [7]$$

What equation [7] implies is that a standard CBA attaches a social importance, or weight, to utility changes that is inversely proportional to the marginal utility of income. As almost all evidence points to the fact that u_{iy} is decreasing in income (e.g., Layard et al. 2008; Deaton, 2008), a standard CBA assigns a higher importance to the interests and preferences of the rich. "Standing" in CBA terminology refers to this discrepancy.

This apparent problem can be addressed with distributional weights designed to give a higher social weight to the monetized welfare changes of individuals with lower income. As Dreze (1998) points out, the need for adjustments or weights for individual welfare changes is well known in economic theory but largely forgotten in practice. Many modern textbooks on environmental valuation (e.g., Freeman et al. 2014) pay scant attention to the use of distributional weights. Some textbooks (e.g., Boardman et al. 2006) do discuss them briefly but nevertheless base most of the theory of CBA on the net benefit criterion. However, the tide seems to be turning, and a more detailed discussion of distributional weights can be found in the latest edition of Boardman et al. (2018), which includes a reference to Article I of this thesis.

Organizations such as the World Bank abandoned the use of weights decades ago, but environmental policy analysts have recently shown renewed interest in them, with Hallegatte et al. (2016) applying them in a report on the poverty induced by disaster risks. On a national level, the UK government officially recommends using distributional weights in CBA (HM Treasury, 2003). Despite this nascent trend, distributional weights are still conspicuous by their absence in practical valuation studies (Adler, 2016; Nyborg, 2014), a notable exception being climate change economics (e.g., Nordhaus & Boyer, 2000; Fankhauser et al. 1997; Tol et al.

2005; Shiell, 2003; Anthoff et al. 2009; Dennig et al. 2015; Anthoff et al. 2016), where weights have been used to account for different income levels between countries, mainly developed and developing countries.

In Article I of this thesis, we provide a theoretical overview of distributional weights and present a case study illustrating how we think they should be included in an environmental CBA.

2.2 Climate change adaptation

Climate change adaptation (hereafter "adaptation") is the process of adjustment to actual or expected climate and its effects. The Intergovernmental Panel on Climate Change (IPCC) defines it as follows: "In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects". (IPCC, 2014a). From an economic perspective, adaptation seeks to reduce the costs related to climate change and, if possible, to turn negative impacts into positive ones (Tol et al. 2005).

Adaptation can take place at different scales: households, firms and the public sector. Even though this thesis focuses on public-sector adaptation, it will be useful at this juncture to describe the decision on how adaptation should take place for each type of economic agent. We follow the framework elaborated by Mendelsohn (2012):

Assuming an individual's preferences can be represented by a utility function, his or her utility is a function of the vector of market commodities $\boldsymbol{X}$ and of the extent of the exogenous climate change factor, indicated by A. The individual then seeks to attain the highest level of utility subject to his or her budget Y and the extent of climate change $A = \bar{A}$.

$$Max\ U(\boldsymbol{X}, A), s.t.\boldsymbol{PX} = Y;\ A = \bar{A}. \qquad [8]$$

Given suitable separability assumptions for the utility function, this results in demand functions for market goods $\boldsymbol{X}$, of which some, $\boldsymbol{X_1}$, are independent of the climate change factor, and some, $\boldsymbol{X_2}$, are dependent on it:

$$\boldsymbol{X_1} = \boldsymbol{X_1}(\boldsymbol{P}, Y) \qquad [9]$$

$$\boldsymbol{X_2} = \boldsymbol{X_2}(\boldsymbol{P}, Y, A) \qquad [10]$$

For the vector of goods $\boldsymbol{X_2}$, consumption is dependent on the climate change factor; these changes in the consumption behavior can be classified as private adaptation. Note that for some class of utility functions, it may be that all demand functions are functions of A, and for some utility functions none of the demand functions is dependent on A. Thus, the variation in consumption is dependent on the preference structure of the individual.

As noted by Mendelsohn (2012), households also consume capital goods, and we can further divide private consumption into consumption goods $\boldsymbol{X}$ and capital goods **K**. For simplicity, we consider a single capital good that is bought in the first period; the good is one that provides utility for the household in not only the current but also later periods. Thus, the individual seeks to maximize his or her lifetime utility:

$$Max \int U_t(X, A, K)e^{-rt}dt \ \ s.t. \int[Y_t - P_x X_t]e^{-rt} - P_k K = 0\,, \ \ s.t. A = \bar{A} \qquad [11]$$

Taking the first-order condition (FOC) of K, we get the following expression:

$$P_K = \int(dU_t(X, A, K)/dK)e^{-rt}dt \qquad [12]$$

Thus, the marginal stream of utility over time from the capital good should equal the price of capital at the optimum. If the marginal utility from the capital is dependent on the climate change factor, the change will affect the choice of capital. This is one type of adaption which might affect an individual's choice whether to buy a residential property for example. The literature related to such choices is growing fast, and Article IV of the thesis broaches the topic through its focus on the interplay of ecosystem services, climate change adaptation and housing prices.

Next, we turn to defining adaptation at the firm level. Let $\boldsymbol{Z}$ denote the input vector, $\boldsymbol{P}$ the input price vector**,** P_1 the price of output, A the climate factor, and $F(\boldsymbol{Z}, A)$ the production function. The firm's maximization problem can then be stated as:

$$\max \pi = P_1 * F(\boldsymbol{Z}, A) - \boldsymbol{PZ} \qquad [13]$$

Much as the consumer had to do in the above case, the firm has to make a long-term capital decision. The firm's problem is then:

$$\max \int[P_1 \ F_t(\boldsymbol{Z}, K, A) - \ \boldsymbol{PZ}]\mathrm{e}^{-\boldsymbol{rt}} - P_k K \qquad [14]$$

The optimum amount of both production inputs and capital inputs can then be derived from this maximization problem. Let $z_1, \ldots, z_n$ denote the inputs. The optimal (non-corner) solutions are:

$$P_{z_1} = \frac{dF(\boldsymbol{Z}, A)}{dz_1} \text{ and } P_k = \int \frac{P_1 \partial F_t(\boldsymbol{Z}, K, A)e^{-rt}}{\partial K}dt. \qquad [15]$$

At the optimum, a firm will set the value of the marginal product of each input to its price. If climate affects the marginal productivity such that F_t is changing in time, a firm will decide on a different amount of inputs at different points of time. The price of the capital good is equated to the discounted stream of revenue from the good and as the stream is dependent on the climate factor, the choice of capital is as well. This is the economic definition of a firm's adaptation where it produces a single good. However, if the marginal productivity of a particular industry changes, it is possible that firms in that industry will shift their output towards other products. (Mendelsohn, 2012).

Finally, there is public adaptation. Many adaptation decisions concern either public policies, public goods or goods with some characteristics of public goods. Articles II and III of the thesis, and to some extent Article IV as well, deal with adaptation that takes place at the public level. The optimal adaptation decision, which involves partial equilibrium for one public good (e.g., OECD, 2018; Mendelsohn, 2012), is to maximize the social net benefits of producing the good:

$$Max \ \ \sum B_i(Q) - C(Q) \tag{16}$$

Again, maximizing with respect to Q, we get the first-order condition for the social optimum:

$$MC(Q) = \sum MB_i \,(Q) \tag{17}$$

This is the classical Samuelson condition (Samuelson, 1954) in the case of a single public good. Later, in section 4.1., we consider the more general case with n public goods and illustrate how the marginal benefit for each individual should be defined.

Equation [17] equates marginal cost to the social marginal benefit. In CBA, the decision is often framed as determining whether to implement a project or policy that can either be implemented or not. The choice is of a discrete nature, where provision level 0 stands for not implementing the project or policy (i.e., maintaining the status quo), and 1 for implementation.

$$\int_0^1 (\sum MB_i \,(Q) - MC) dq > 0 \tag{18}$$

Thus, efficient adaptation requires a CBA to assess the benefits and costs of implementing a particular adaptation policy or project. CBA is the main tool to assess public adaptation policies (UN, 2011; Logar & Van den Bergh, 2013; IPCC, 2014b; Leary, 1999). As illustrated by Tol et al. (2005) a benevolent world dictator would take both adaptation and mitigation into account simultaneously when choosing the optimal climate policy. However, in the real world, GHG emissions are usually taken as an exogenous factor when choosing between adaptation options. Adaptation is primarily a matter addressed by local managers of natural resources, individual households and companies in the context of a regional economy and society (Tol et al. 2005).

Finally, uncertainty is an inherent feature of adaptation, even to extent that the uncertainty related to climate change adaptation decisions is referred to as *deep uncertainty*. Deep uncertainty can refer to any of three contingencies: 1) there is no clear consensus on which models should be used to assess the future; 2) the probability distribution of key parameters is unknown; or 3) the value of outcomes is uncertain (Hallegatte et al. 2012). It has been suggested that, if any of these applies, robust adaptation strategies should be used as a basis for decision making rather than the expected value of investment decisions (Dessai and Hulme, 2007; Hallegatte, 2009; Hallegatte et al. 2012). Robust adaptation options include (Hallegatte, 2009) *no-regret measures,* which create benefits even in the absence of climate change; *reversible measures*, which are easily retro-fitted if climate projections prove to be wrong; *safety margin measures,* which reduce the vulnerability of a system at a low or no cost; *soft measures,* which refer to institutional or financial changes; *reduced time horizon measures*, which involve reducing the lifetime of an investment; and strategies which have synergies with mitigation. In Article III we follow the line of thinking that favors robust adaptation measures and give an example of one such adaptation option.

In Article IV, uncertainty has been accommodated in the model by specifying a set of contingencies that describe different possible paths. Contingencies can be thought of as different future scenarios and should at least represent the possible outcomes between the two extremes. (Boardman et al. 2018). Article IV presents a high-benefit/low-cost scenario and a low-benefit/high-cost scenario. In addition to showing the lower and higher bounds for the benefits and for the costs, we make assumptions about the likely shape of the distribution of each benefit and cost item and state the expected value.

Article II applies a Monte Carlo simulation, a widely used method to analyze the impacts of uncertainty in parameter values on the results of a CBA. If uncertainty could be represented by contingent outcomes, one could simply present the results of a CBA using different scenarios, as is done in Article IV. However, it is often the case that the benefits and costs in a given instance are dependent on a number of different parameter values that may or may not be dependent on each other. Where this is the case, a distribution is specified for each parameter value, a set of random draws from each distribution is taken, and the trial is repeated a number of times. We follow the suggestions of Boardman et al. (2018) when specifying the distributions. The resulting histogram can then be used to calculate statistics about the outcome, such as expected values, range of the Net Present Value (NPV), and the significance of the results.

2.3 Urban Ecosystem Services

Natural resources can be used as inputs in production or can be directly consumed. The use of natural resources for the wellbeing of people is referred to as provision of ecosystem services (e.g., de Groot et al. 2002). There are many classifications of such services (e.g., Costanza et al. 1997; Wallace et al. 2007; de Groot et al. 2002), with categories including those used in the production of traded goods such as raw materials and the production of food and those directly consumed by people, examples being cultural and recreational services. Many ecosystem services exhibit the characteristics of a public good to at least some extent; that is, they are non-excludable and non-rival, whereby one person's consumption of these services does not reduce another's, and no one can be excluded from consuming such services.

The total economic value of ecosystem services can be divided into five function groups: direct use value, indirect use value, option value, bequest value and existence value (e.g., de Groot et al. 2002). The first two categories include use values from tangible services, and their value is easier to evaluate, for such services include physical (and marketed) products such as food and timber. Option values include future, uncertain use values such as those in the field of genetic prospecting. Intangible bequest and existence values are the hardest to evaluate, as they include benefits such as cultural heritage and indigenous rights. (e.g., Costanza et al. 1997). An extensive valuation of ecosystem services is challenging, and a variety of different methods have been developed for different purposes and situations. (See Costanza et al. (1997) for the first comprehensive review of these). Article IV places a special emphasis on the valuation of non-use services.

These public good characteristics of ecosystem services again lead to Pareto inefficiency in the competitive equilibrium; if the service or resource is non-excludable and rival, that is, a common pool resource, overuse of the asset might persist, a situation known as a tragedy of the commons (Hardin, 1968). The word “might” in the previous sentence refers to the fact that in many cases institutions themselves can correct overuse through evolving norms, but often this is not enough to prevent overuse of common-pool resources. (Ostrom, 1999). In the case of non-rival goods, it is inefficient to exclude anyone from use of the services, as the marginal cost of provision is zero. Non-excludable goods suffer from the free-rider problem, in which an individual is not willing to participate in the costs of providing a good and resources are misallocated to private goods (e.g., Olson, 1965). As the markets fail to optimally provide ecosystem services to individuals, it is often the task of the society to decide on their provision (e.g., Farber et al. 2002). Again, at the social optimum, the marginal cost of provision should equal the marginal benefits (Samuelson, 1954).

A city can be defined either as a single ecosystem or be seen as composed of several individual ecosystems. The term “ecosystem” is used here quite freely to cover all natural green and blue areas in a city, even if street trees are too small to be considered ecosystems by ecologists (Bolund and Hunhammar, 1999). Bolund and Hunhammar (1999) have identified seven different urban ecosystems: street trees, lawns/parks, urban forest, cultivated land, wetlands, lake/sea, and streams. Green roofs and green walls could be added to this list (Nurmi et al. 2016). The trade-off is usually between the benefits of ecosystem services, on the one hand, and opportunity costs of land and the costs of creating and maintaining the services, on the other. As the benefits of many ecosystem services are usually non-excludable and non-rival while the costs, especially in urban areas, are private, the social optimum is not achieved. Article IV presents an illustrative case in this regard in which green roofs create public benefits while the installation costs are borne by a private developer or home-owner. The problem can be studied with a formal model of private provision of a public good (e.g., Bergstrom et al. 1986):

Consider a case of two individuals, a market good X, and an ecosystem service q. The aggregate level of the privately provided ecosystem good is equal to the sum of private provision such that $q = q_1 + q_2$. Each consumer utility function is a function of both the quantity of the private good and the aggregate quantity or quality of the ecosystem service. All of the individuals' income is spent on either the private good or voluntary provision of ecosystem goods with private opportunity costs such that U^1=$u^1(\hat{y}, q)$, where $\hat{y}_1 = y_1 - pq_1$ is the disposable income for the consumption of market good X. Solving the problem for individual 1 by taking the first order condition with respect to q_1 yields the following:

$$-\frac{\partial u^1}{\partial \hat{y}_1} p_q + \frac{\partial u^1}{\partial q} = 0 \qquad [19]$$

such that at optimum:

$$p_q = \frac{\frac{\partial u^1}{\partial q}}{\frac{\partial u^1}{\partial \widehat{y_1}}} = MRS_q^1 \qquad [20]$$

Thus, at the private optimum, the individual equates the price of provision to the marginal rate of substitution between the ecosystem service and his and her income, which can be interpreted as the marginal WTP for the ecosystem service.

However, as the Samuelson condition requires, at the social optimum the price should equal the sum of marginal WTP over the population such that:

$$p_q = MRS_q^1 + MRS_q^2 \qquad [21]$$

Clearly, at the private optimum, less of the ecosystem service is provided than at the social optimum.

3 THE MICROECONOMIC THEORY UNDERLYING COST-BENEFIT ANALYSIS

In CBA, changes in individuals' wellbeing are usually assessed in monetary terms. This section develops a formal framework for such an assessment. The analysis is built on the preference-based approach. As the standard approach for defining monetary welfare changes is modified into what is known as a virtual problem in section 3.2., a detailed description of the standard problem is provided first.

A utility function such as $u: \boldsymbol{x} \rightarrow R$ provides a useful tool for representing the preference relation $\succcurlyeq$, as mathematical programming techniques can be used to analyze the consumer's problem. A utility function is a mapping of different commodity vectors $\boldsymbol{x}$ into a real number that denotes ordinal utility. Its application requires several assumptions: the preference relation needs to be complete, transitive and continuous in order to prove that a continuous utility function exists. As the utility function is a mapping from the commodity space **X** to a real number R, it would be tempting to refer to the marginal value as the marginal change occurring in u when a component of the commodity vector (e.g., x_i) changes. However, this is not possible since the utility function u represents only ordinal utility and the numerical values of utility cannot be equated with or likened to the desired monetary units.

The standard utility maximization problem (UMP) can be stated as follows:

$$Max\ u(x), s.t. \boldsymbol{p} * \boldsymbol{x} \leq y \qquad [22]$$

With positive prices and a continuous utility function, a solution $\boldsymbol{x}^*(\boldsymbol{p}, y)$ exists and is single-valued if preferences are strictly convex. Once we have solved the UMP, we can place the solution $\boldsymbol{x}^*(\boldsymbol{p}, y)$ back into the utility function. The new maximum value function is called an indirect utility function v(**p**,y). Like the utility function, the indirect utility function is not unique, for any strictly increasing transformation represents the same preferences.

If there are L (traded) commodities, **x** can be viewed as a point in the commodity space R^L. For the formal treatment of public goods or ecosystem services (i.e., *non-market goods)*, a new disjoint finite set Q is introduced, the quantities in which the consumer takes as exogenous and which is represented by the vector **q**. Assuming that there is a utility representation of the consumer's preferences over the set $X * H$ of $u(\boldsymbol{x}, \boldsymbol{q})$ $u: X * Q -> R$, we can again solve the optimal commodity vector for the consumer. Optimal solution $\boldsymbol{x}^*$ is now a function of the exogenous **q** as well and can formally be stated as $\boldsymbol{x}^*(\boldsymbol{p}, \boldsymbol{q}, y)$; the corresponding indirect utility function $v(\boldsymbol{p}, \boldsymbol{q}, y)$ is now the maximum value function (Willig, 1976; Mäler, 1974; Hammond, 1994).

A special class of indirect utility functions is needed in order to construct money metric utility functions. Starting from the indirect utility function $v(\boldsymbol{p}, \boldsymbol{q}, y)$, choosing a reference price vector $\boldsymbol{p_0}$, reference income

y_o and reference vector of non-market goods $\boldsymbol{q_0}$, and then setting up an expenditure function $e(\boldsymbol{p}, \boldsymbol{q}, v(\boldsymbol{p_0}, \boldsymbol{q_0}, y_o)$, we obtain a function showing the income required to reach the utility level $v(\boldsymbol{p_0}, \boldsymbol{q_0}, y_o)$. This expenditure function is strictly increasing as a function of the level $v(\boldsymbol{p}, \boldsymbol{q}, y)$ and can be viewed as a money metric indirect utility function. (e.g., Hammond, 1994).

3.1 Compensating variation and equivalent variation

The money metric utility function can now be used to define the two most relevant concepts in CBA: compensating variation (CV) and equivalent variation (EV). Mäler (1974) was the first to define these concepts for accommodating changes in the amount of non-market goods. First, for the sake of simplicity, we treat the price vector as a constant and omit it from the analysis. Second, again for simplicity, we consider only one non-market good at a time and denote the quantity of that good by q such that q_0 is the level of the good before the change, and q_1 that after the change. Third, for notational simplicity, we write $v(\boldsymbol{p_0}, q_0, y_o) = u_0$ and $v(\boldsymbol{p_0}, q_1, y_o) = u_1$.

For a gain in environmental quality/quantity (from q_0 to q_1), CV measures the maximum willingness to pay (WTP) to obtain the change, and EV the minimum compensation that an individual is willing to accept (WTA) to forego the change. CV and EV are now defined using the expenditure functions $e(q, u)$:

$$CV = e\left(q_{0,} u_0\right) - e(q_1, u_0) \quad [23]$$

$$EV = e\left(q_{0,} u_1\right) - e(q_1, u_1) \quad [24]$$

Alternatively, we can define them directly with the use of indirect utility functions, such that:

$$v(q_1, y - CV) = v(q_0, y) \quad [25]$$

$$v(q_1, y) = v(q_0, y + EV) \quad [26]$$

Clearly, both CV and EV are equilibrium values that return individual to the reference utility level. They are dependent on both the original quantity of the non-market good in question and income, thus allowing comparative statics to be developed. Two tasks are of particular interest here: the first is to ascertain how the two measures differ and which should be used in different situations; the second is to establish how income affects these measures, as the outcome of this analysis determines the standing in the CBA, a concept derived in section 2.1.

Assuming $u_1 > u_{0,}$ CV tells us the difference between the expenditure needed for an individual to reach utility level u_0 without an increase in the non-market good and that needed to reach utility level u_0 with an increase in the good. Clearly, this is a positive difference, as more of market goods (higher income) are needed to compensate for the lower quantity of the non-market good. This is also the maximum that an individual should be willing to pay (WTP) for the change. With the same assumption, EV tells us the difference between the expenditure needed to reach the new (higher) utility level u_1 with the original (worse) and the new (improved) level of the non-market good. This is the minimum compensation that an individual should be willing to accept (WTA) not to get the improvement.

3.2 Comparative statics

The first point to focus on is the disparity between CV and EV. As seen from equations [23]-[26], the only difference between CV and EV is the reference utility level based on which the difference between the required expenditure levels is calculated. For CV, the original utility ($u_{0,}$) without an increase in the quantity of the non-market good is the status quo, while for EV the utility level u_1 following the increase in the quantity of the non-market good is the status quo. This also provides a rule of thumb for choosing the right measure: If an individual is entitled to the increase, EV should be used; if he or she is not automatically entitled to the increase, CV is the appropriate measure (e.g., Mitchell and Carson, 1989). However, there might be cases where strict legal entitlements differ from privileges prescribed by the social norms of the community. Particularly in these cases, care should be exercised in choosing the right measure (e.g., Knetsch, 2006; Whittington et al. 2017).

Much of the relevant literature in fact focuses on the disparity between the measures. This literature is rich, and there is extensive evidence that the two measures can differ considerably (reviewed, for example, in Horowitz & McConnell, 2002) and, depending on the one chosen, the resulting CBA will suggest very different policy recommendations. This literature can be divided roughly into three categories reflecting scholars' approach to understanding the disparity: There are those seeking 1) a neoclassical explanation consistent with assumptions of transitivity and completeness, put forward in early studies such as Willig (1976), Randall and Stoll (1980) and Hanemann (1991), those investigating 2) behavioral reasons (e.g., Tverksy & Kahneman, 1991) and those looking for 3) empirical evidence of the disparity (e.g., Horowitz & McConnell, 2002; Sayman & Onculer, 2005).

The subsequent sections of the thesis consider the neoclassical explanation of the disparity between CV and EV, as the conditions that create the disparity are precisely the same ones that create the income effect for both CV and EV. This effect, in turn, determines which income groups benefit from different public policies and projects.

The following condition ensures that for an increase in the quantity or quality of a non-market good, EV is higher than CV: If the function $e(q, u)$ is continuous, it is both a necessary and sufficient condition that:

$$\frac{\partial e(q,u)}{\partial -q \partial u} > 0 \qquad [27]$$

The proof of this condition is found in the Mathematical Appendix. The term $\partial - q$ represents a marginal decrease in the non-market good. This condition can also be referred to as the *complementary condition* between market goods and a non-market good. Intuitively it means that a decreasing level of a non-market good is increasingly hard to compensate for with market goods. It can also be interpreted as an increasingly higher marginal rate of substitution between the non-market good and the market goods at higher indifference curves.

Next, the condition under which the income has a positive effect on CV (or EV) is stated: If the function $e(q,u)$ is continuous and assuming $\frac{du}{dy} > 0$, it is both a necessary and sufficient condition that:

$$\frac{\partial e(q,u(y))}{\partial - q \partial u} > 0 \quad [28]$$

The proof is again in the Mathematical Appendix. Intuitively, this means that the wealthier an individual becomes, the more he or she is willing to give up wealth for the same increase in the non-market good. However, as the reference utility is only dependent on the reference price vector, the reference level of the non-market good, and income, the condition is exactly the same as that in equation [27].

Thus, whenever $EV > CV$, it also holds that $\frac{\partial WTP}{\partial y} > 0$. This would be easy to verify if the preferences of the individual were known and the expenditure function could be derived. Unfortunately, preferences regarding public goods are usually not recoverable (Ebert, 1998) and the conditions on the underlying preferences for a positive income effect (or the disparity between the two measures) are best studied using a formal framework that connects the sign and magnitude of the income effect on the sign of measures that are familiar to most economists.

3.3 Income elasticities

The distributional issues related to CBA form one of the central thematic areas examined in this thesis. How the outcome of a CBA is affected by individuals' income differences is obviously crucially dependent on how income affects CV and EV. In addition, it can be proven that the benefit incidence is directly linked to the income elasticity of WTP ($\eta(WTP,y)$ as follows (Ebert, 2003):

$if\ (\eta(WTP,y) > 1$, then $\frac{\partial WTP(\boldsymbol{p},q,y)/y}{\partial y} > 0$; the benefits are distributed progressively. [29]

$if\ (\eta(WTP,y) < 1$, then $\frac{\partial WTP(\boldsymbol{p},q,y)/y}{\partial y} < 0$; the benefits are distributed regressively. [30]

$if\ (\eta(WTP,y) = 1,$ then $\frac{\partial WTP(\boldsymbol{p},q,y)/y}{\partial y} = 0$; the benefits are distributed proportionally. [31]

The same definition would apply if we used WTA as a measure of the monetary benefits. The correct measure for analyzing the benefit incidence (and the income effect more generally) is thus the income elasticity of WTP and WTA. To be able to derive the connection between an individual's preferences and income elasticity, we apply the model originally developed by to study the welfare impacts of rationed goods (Neary and Roberts (1980)) and subsequently adapted to study the welfare impacts of non-market goods (e.g., Hanemann, (1991) Flores and Carson (1997) and Ebert (2003)).

In the model, there are n market goods available, the quantities of which are denoted by a vector, **x**, as well as a non-market good q, or multiple non-market goods whose quantities are denoted by a vector, **q**. The non-market good or goods are to be understood as pure public commodities, whose quantity/quality consumers take as exogenously determined. Consumers have preferences, which can be represented by a utility function $U(\boldsymbol{x}, \boldsymbol{q})$.

First, we describe the traditional consumer utility maximization problem:

$$\max U(\boldsymbol{x}, \boldsymbol{q})\ s.t. \boldsymbol{px} = \boldsymbol{Y}, \boldsymbol{q} = q_0 \quad [32]$$

As a solution we get the observable conditional Marshallian demand functions $x_i(\boldsymbol{p}, q, y)$, i=1…, n, as explained earlier. Again, by inserting the demand functions back into the utility function we get the indirect utility function $v(\boldsymbol{p}, q, y)$ and, using the basic duality properties, the expenditure function $e(\boldsymbol{p}, q, u)$. As before, the analysis begins by looking at a single non-market good. Now a virtual problem can be defined. In the virtual problem, both x and q are treated as market goods, and the consumer's problem is:

$$\max U(\boldsymbol{x}, q)\ [11]\ s.t. \boldsymbol{px} + p_v \mathrm{q} = y_v \quad [33]$$

The subscript v marks the virtual problem; y_v is the virtual income, which is the level of income that would allow the consumer to buy exactly the same amount of both goods that were attained in the standard problem. As a solution we get the following virtual Marshallian demand functions:

$$x_{vi}(\boldsymbol{p}, p_v, y_v)\ \ i = 1 \ldots, n \text{ and } q_v(\boldsymbol{p}, p_q, y_v\ ) \quad [34]$$

Next, the price and income levels that would make these solutions coincide with the solutions to the standard problem in equation [32] are defined such that the consumer would willingly buy exactly the same amounts of both market goods and the non-market good consumed in the standard problem. The answers are termed *virtual price* p_v and *virtual income*, with $y_v = y + p_v q_0$. As the virtual price is by definition the exact price that the consumer would be willing to pay at the margin q_0, it equals the marginal WTP. We can also define the (utility constant) Hicksian-compensated virtual price $p_v^c(\boldsymbol{p}, q_0, u)$ by differentiation of the virtual expenditure function with respect to $-q$, obtaining $\frac{\partial e}{\partial -q} = p_v^c(p, q_0, u)$. Based on these procedures the following identity can be defined:

$$q_0 = q_v(\boldsymbol{p}, p_v(\boldsymbol{p}, q_0, y), y + p_v q_0\,) \qquad [35]$$

Equation [35] then makes it possible to define two relevant income elasticities: income elasticity $\eta(q_v, y)$ of virtual demand q_v and income elasticity $\eta(p_v, y)$ of virtual price p_v (Flores & Carson, 1997), the latter sometimes referred to as the price flexibility of income (Randall & Stoll 1980 and Hanemann, 1991).

$$\eta(q_v, y) = \frac{\partial q_v(\boldsymbol{p}, p_v(\boldsymbol{p}, q_0, y), y + p_v q_0\,)}{\partial y} \frac{y + p_v q_0}{q_v(\boldsymbol{p}, p_v(\boldsymbol{p}, q_0, y), y + p_v q_0\,)} \qquad [36]$$

$$\eta(p_v, y) = \frac{\partial p_v(p, q_0, y)}{\partial y} \frac{y}{p_v} \qquad [37]$$

Equation [37] can be used to derive an expression that makes it possible to derive a mathematical connection between the sign of the income effect and the sign of the derivate of the ordinary demand function with respect to income. The derivation of these concepts is found in the Mathematical Appendix. In the case of a single non-market good, Hanemann (1991) used equation [37] to derive the following equation:

$$\frac{\partial p_v}{\partial y} = \frac{-\frac{\partial q_v}{\partial y}}{\left(\frac{\partial q_v}{\partial y} q_0 + \frac{\partial q_v}{\partial p_v}\right)} \qquad [38]$$

By Slutsky decomposition, the denominator $\left(\frac{\partial q_v}{\partial y} q_0 + \frac{\partial q_v}{\partial p_v}\right)$ can be expressed as the Hicksian own price derivate $h^q_{p_v}(p, p_{v,} v(p, q_0, y)$, which is always negative. Thus, in the case of a normal good, $-\frac{\partial q_v}{\partial y}$ is negative, which makes the virtual price increasing with respect to income. Intuitively this means that if the non-market good were available as a market good and were classified as a normal good, the marginal WTP of that good would be increasing in income.

Equation [38] can also be converted into elasticity form. Using some of the algebra presented in the Mathematical Appendix, the following expression is derived (Hanemann, 1991):

$$\eta(p_v, y) = \frac{\eta(q_v, y)}{\sigma_0}, \qquad [39]$$

where $\eta(p_v, y)$ is the (desired) income elasticity of the virtual price (or marginal WTP) and σ_0 is the aggregate Allen-Uzawa elasticity of substitution between q and other goods. Thus, the income elasticity of the virtual price is dependent on the ordinary income elasticity of demand and the substitutability between q and the market goods. If the substitutability between the market goods and environmental good is perfect, then $\sigma_0 = \infty$ and the income elasticity is zero. This result stands to reason, as the price of the substitute sets the upper limit for the willingness to pay for the public/environmental good. In this case, the income has no effect on the consumer's WTP. This also complements the result derived in section 3.2 in equations [27]-[28] regarding the complementarity condition between market and non-market goods.

Flores and Carson (1997) extended the analysis of Hanemann (1991) to a problem involving multiple non-market goods and showed that the common-sense logic noted above no longer applies. Rather, the elasticities of the virtual prices in the case of two non-market goods can be expressed as:

$$\begin{pmatrix}\eta_1(p_v, y)\\ \eta_2(p_v, y)\end{pmatrix} = -\begin{pmatrix}\sigma_{11} & \sigma_{12}\\ \sigma_{21} & \sigma_{22}\end{pmatrix}^{-1}\begin{pmatrix}\eta_1(q_v, y)\\ \eta_2(q_v, y)\end{pmatrix} S_x^v , \quad [40]$$

where σ_{ij} is the Hicksian cross-price substitution elasticity of demand for q_i and q_j and S_x^v is the budget share of market goods, defined as $S_x^v = \frac{y}{y+p_v q}$.

As explained, the virtual price equals the marginal WTP at the status quo, or q_0 (Ebert, 2003). At the margin, the Marshallian virtual price (income constant) and the Hicksian virtual price (utility constant) are identical, and so are the income elasticities. Also of interest are the non-marginal changes along the dimension of non-market good quantity but as CV and EV are utility-constant measures, the expenditure on market goods does not match the initial income level as we move along that dimension. The virtual prices no longer match, nor do their elasticities. By adjusting equation [40] to take this into account, the income elasticities of virtual prices can be written as follows: (Flores & Carson, 1997)

$$\begin{pmatrix}\eta_1(p_v^c, y)\\ \eta_2(p_v^c, y)\end{pmatrix} = -\begin{pmatrix}\sigma_{11} & \sigma_{12}\\ \sigma_{21} & \sigma_{22}\end{pmatrix}^{-1}\begin{pmatrix}\eta_1(q_v, y)\\ \eta_2(q_v, y)\end{pmatrix} S_x^v \left(\frac{y}{e(p,Q,U}\right) * \frac{\partial e(p,q,u)}{\partial u}\frac{\partial u}{\partial y} \quad [41]$$

Next, it is noted that $\frac{\partial p_v^c(p.q,u)}{\partial y} = \eta(p_v^c, y) * \frac{p_v^c}{y}$, allowing the income elasticity of WTP to be expressed in terms of the elasticity of the Hicksian virtual price (Ebert, 2003):

$$\eta(WTP, y) = \frac{\partial WTP}{\partial y}\frac{y}{WTP} = \frac{y}{WTP}\int_{q_0}^{q_1}\eta(p_v^c, y) * \frac{p_v^c}{y} = \frac{1}{WTP}\int_{q_0}^{q_1}\eta(p_v^c, y) * p_v^c = \frac{\int_{q_0}^{q_1}\eta(p_v^c, y) * p_v^c}{\int_{q_0}^{q_1} p_v^c(p,q,u)dq} \quad [42]$$

Intuitively, the income elasticity of WTP is then an average income elasticity of sorts of the Hicksian virtual price between q_0 and q_1. Drawing on this insight, it can be shown (Flores & Carson, 1997) that:

$$\eta_l \leq \eta(WTP, y) \leq \eta_h, \quad [43]$$

in which η_l (η_h) is the minimum (maximum) income elasticity of the compensated virtual price over the range $[q_0, q_1]$.

The income elasticity of WTP then encompasses the income elasticities of demand for all rationed goods, inverted cross-price demand substitution elasticities, and the share of virtual expenditure devoted to market goods. (Flores & Carson, 1997; Ebert, 2003).

The theory presented thus far does not in itself afford us any ready insights that would us to determine whether non-market goods (in the case of more than one non-market good) are inferior ($\eta(WTP, y) < 0$), normal ($\eta(WTP, y) > 0$) or luxury goods ($\eta(WTP, y) > 1$). This determination was straightforward in the case of a single non-market good.

Fortunately, many studies directly measure the income elasticity of WTP for environmental goods; it is usually estimated from a WTP function that attempts to explain the variation in WTP by regressing WTP on explanatory variables, including personal income. Using such a function, the income elasticity of WTP can be estimated as $\frac{\partial WTP}{\partial y}\frac{y}{WTP} = \frac{\partial(lnWTP)}{\partial(lny)}$. A log-log specification of the relationship between WTP and income yields a coefficient value that can be interpreted as an estimate of the income elasticity of WTP (Jacobsen & Hanley, 2009). This approach is applied in Article I of the thesis. The analysis and earlier results indicate that for most environmental goods the income elasticity is higher than 0 but lower than 1. In Article I we connect the income elasticity of WTP and the distributional weights and show that where income elasticity is below unity, the weighted benefits surpass the unweighted benefits. This finding bears on the discussion related to aggregation of individual welfare changes, which constitutes the topic of the next section.

4 AGGREGATION AND SOCIAL CHOICE RULES

In addition to measuring the monetary utility changes for individuals, CBA carries out aggregation of those changes over the relevant population. Yet what is meant by "relevant population" is in many cases not at all clear, contentious issues being how the aggregation should take place over populations across national borders and over different generations (e.g., Whittington & McRae, 1986). Article I takes up the international aspect of the aggregation problem. Here, we study the problem of aggregation from the neoclassical point of view in a stylized economy with no international welfare effects to consider, and assume that government is trying to maximize the welfare of its citizens.

4.1 Optimal non-market good provision

As a starting point, it will be helpful to recall the traditional Samuelson Rule (Samuelson, 1954), which states the optimal conditions for the provision of public goods in the case of multiple non-market goods:

$$\frac{\sum_i MRS^i_{q_1}}{p_1} = \frac{\sum_i MRS^i_{q_2}}{p_2}, \quad [44]$$

where $MRS^i_{q_1}$denotes the marginal rate of substitution between a non-market good and income, which can be interpreted as the marginal WTP.

If this were the case, we would simply add up the individuals' monetized utility changes. However, it can be shown that in most cases this aggregation rule is not applicable. We follow here the analysis by Johansson-Stenman (2005).

Individuals attain utility from the consumption of market goods y, public goods $q_1, \dots, q_m$ and leisure l as follows:

$$U^i = u^i(y^i, l^i, q_1, \dots, q_m) \quad [45]$$

An individual has a time budget ω, such that $l^i = \omega - L^i$. His or her net income per hour of work is given byw^i, and consumption by $y^i = w^i L^i - T(w^i L^i)$. T is a tax function and is applies to gross income $w^i L^i$ rather than the hourly wage rate w^i, as the latter rate is not directly observable to the government.

Taking these conditions together, the individual maximization problem with respect to the choice of working time L^i is:

$$\max u^i(w^i L^i - T(w^i L^i), \omega - L^i, q_1, \dots, q_m) \quad [46]$$

Differentiation with respect to L^i and taking the first-order condition (FOC) yields:

$$\frac{\partial u^i}{\partial y^i}(w^i - w^i \frac{\partial T}{\partial (w^i L^i)}) + \left(-\frac{\partial u^i}{\partial (l^i)}\right) = 0 \quad [47]$$

or $\frac{\partial u^i}{\partial y^i} w^i\left(1 - t^i\right) = \frac{\partial u^i}{\partial l^i}$, in which $t^i = \frac{\partial T}{\partial (w^i L^i)}$ the he marginal tax rate for individual i. This can be compared to the social optimum: at the margin, an individual is indifferent between working one hour more or one hour less. However, if the individual chooses to work one hour more, the society realizes an increase in tax income of $t^i w^i$. Accordingly, at the social optimum people should work more than at the private optimum.

The government maximizes the SWF:

$$w(U^1, \dots U^n) \quad [48]$$

with the public budget requirement:

$$\sum_i T\left(w^i L^i\right) = \sum_m p_m q_m + R_0, \quad [49]$$

in which R_0 stands for the allowed deficit. Consequently, the government's maximization problem can be stated with the following Lagrangian (Kuhn-Tucker algorithm needed only if the monotonicity assumption is relaxed):

$$L = w(U^1, \dots U^n) + \lambda\left(\sum_i T(\, w^i L^i\right) - \sum_m p_m q_m - R_0) \quad [50]$$

The FOC for arbitrary public good 1 yields:

$$\sum_i \frac{\partial w}{\partial u^i}\frac{\partial u^i}{\partial q_1} + \lambda\left(\sum_i t^i w^i \frac{\partial L_i}{\partial q_1} - p_1\right) = 0 \quad [51]$$

Rewriting the FOC by denoting the net taxes collected by the government R such that $\frac{\partial R}{\partial q_1} = \sum_i t^i w^i \frac{\partial L_i}{\partial q_1}$, yields the following:

$$\sum_i a^i\, MRS^i_{q_1} = \lambda\left(p_1 - \frac{\partial R}{\partial q_1}\right), \quad [52]$$

where a^i is the social marginal utility of income $\frac{\partial w}{\partial u^i}\frac{\partial u^i}{\partial y^i}$ and $MRS^i_{q_1} = \frac{\partial u^i}{\partial q_1} / \frac{\partial u^i}{\partial y^i}$ the marginal willingness to pay for the non-market good.

Combining this condition for public goods 1 and 2 implies:

$$\frac{\sum_i \alpha^i MRS^i_{q_1}}{\left(p_1 - \frac{\partial R}{\partial q_1}\right)} = \frac{\sum_i \alpha^i MRS^i_{q_2}}{\left(p_2 - \frac{\partial R}{\partial q_2}\right)} \quad [53]$$

This can be compared to the traditional Samuelson (1954) Rule in equation [44], which underlies the rationale of unweighted cost-benefit analysis.

The two deviations from the Samuelson Rule are the factors α^i and $\frac{\partial R}{\partial q_1}$, the revenue effect of raising funds for producing the public goods. The alpha factor is analogous to the weighting of individual monetary utility changes, as is done in Article I. The marginal revenue factor in the denominator either adds to the social price of the public good (if on the margin people work less) or reduces the social price of the public good (if on the margin people work more). Johansson-Stenman (2005) notes that one cannot deduce from this equation whether it is optimal, compared to the outcome using the unweighted rule, to over-provide a public good that is preferred by the poor: even though the weight factors increase the weight of the changes of wellbeing of the poor (and thus the aggregate benefits if income elasticity is below unity), it may be that provision of the public good preferred by the poor results in a decrease in tax revenue. How these two effects interact depends on the preference structure of the individuals and is the reason why different assumptions on the utility formulation lead to different conclusions as to whether weight factors should be applied. First, consider a preference structure in which an individual's utility is weakly separable in public goods. His or her utility function can then be written in the form:

$$U^i = u^i(f(y^i, l^i), q_1, \dots, q_m) \qquad [\qquad [54]$$

In this preference structure, the marginal rate of substitution between leisure and private consumption is unaffected by the provision of public goods; the labor supply is independent of public goods, whereby $\frac{\partial L_i}{\partial q_1} = 0$ for all individuals. The results obtained from the maximization of the SWF then reduce to:

$$\frac{\sum_i \alpha^i MRS^i_{q_1}}{(p_1)} = \frac{\sum_i \alpha^i MRS^i_{q_2}}{(p_2)} \qquad [55]$$

Consequently, in the case of separability between public goods and private consumption and leisure, one should compare the weighted sums, supporting the claim put forward in Article 1.

Next, consider a utility function which is separable in leisure but not in public goods:

$$U^i = u^i(f(y^i, q_1, \dots, q_m), l^i) \qquad [56]$$

As opposed to the earlier case, under these conditions it is not optimal to use weights, but rather to apply the unweighted Samuelson Rule. The intuition goes as follows: by keeping the value of the function f unchanged but modifying y^i such that it is reduced with income tax function T by the exactly the same amount as $MRS^i_{q_{1y}}$ increases the total WTP for public goods, the individual's labor supply choice is unaffected. The reason for is that the amount of leisure chosen is affected by the value of f only, not the amount of money or public goods. Now the government should provide public goods $q_1, \dots, q_m$ to provide Pareto improvements until $\sum_i MRS^i_{q_1} = p_1$ (Boadway and Keen, 1993; Johansson-Stenman, 2005). In this case, the weights are redundant to the analysis.

Yet, as pointed out by Boadway (2016) and others, there is no empirical evidence that the latter specification of the utility function is correct. Moreover, the debate is mainly a theoretical one, especially if the public good is financed from a pre-collected budget and has no effect on the tax schedule. Finally, even if distributional weights are not taken into account in the choice of a project and one believes that the assumption of separability in leisure is a valid one, weights should be included in the analysis when choosing the tax-transfer system (Adler, 2016; Boadway, 2006). In reality, a government has only very limited options in raising funds for public good provision. In the case of large projects, an expanded schedule of policy options should be considered, including ones with feasible tax-transfer schedules. (Adler, 2016).

The implications of the theoretical debate can be summarized in the following practical guidelines:

1) In the case of projects that do not result in changes in the tax schedule, distributional weights should be used (Johansson-Stenman, 2005).

2) If the decision maker can simultaneously change the tax-transfer schedule, a menu of policy options should be analyzed, including combinations with feasible tax schedules. There may be a Pareto-dominant option which is feasible compared to the one suggested by the weighted CBA. However, the analyses should use weights and adjust for the distortionary effects of taxes. (Adler, 2016).

4.2 CBA as an element in social decision making

From the analysis above, it can be noted that the theory of optimal public good provision and CBA are based on the assumption of a benevolent dictator who maximizes the social welfare. The purpose of this assumption, in practical terms, is to derive a decision rule that would allow us to choose one alternative over others rather than to provide information to someone else who is making the decision.

In the case of a project involving one public good, the social choice rule, whether derived from the Samuelson Rule or from the weighted decision-rule in equation [55], can be expressed as follows (e.g., OECD, 2018; EU, 2016):

$$\sum_{i,t} a_i(B_i - C_i)\,(1+r)^{-t} > 0, \qquad [57]$$

where a_i denotes the distributional weights ($a_i = 1$, for 1,2,…,i if weights are not applied), and r the chosen discount rate. A social choice rule, or a collective choice rule (e.g., Sen, 1970), is a rule that ranks different states of the world. Strictly speaking, if equation [57] is used as it reads, the only way to apply it is to implement the projects that satisfy the rule. However, as noted in section 1.2, in the policy context CBA is rarely used strictly as a social choice rule, but rather (with mixed practices) serves as one of the elements affecting the policy choice.

If we take the view that CBA constitutes only part of the information for decision making, an argument can be made that the use of welfare weights makes it harder to explain what has been done (Nyborg, 2014). However, in contrast, it could be argued that inclusion of the weighted results of a CBA, for example in the sensitivity analysis, would improve the information base for the decision-making process by revealing effects that are highly relevant for public decision making, which aspires to account for social justice. In our view, presenting the weighted results would show information related to income elasticity, income distribution and distribution of benefits in a denser and more understandable way than other alternatives and would serve to showcase how important distributional concerns are. However, at the time of writing, CBA is rarely employed in such a transparent way in decision making. If only listed qualitatively, distributional effects can be used to justify almost any policy choice. Explicit use of weights would perhaps mitigate this problem to some extent.

Nyborg (2014) states that a certain list of expected impacts should be compared to the project costs in what she calls a “cost-impact analysis”. The monetized benefits and costs are a part of that list. The benefits in a cost-impact analysis are also expressed in physical impacts, such as the number of birds saved, the number of people saved, and like outcomes. Moreover, legislative and political issues should also be stated explicitly. The list of unweighted benefits of a project or policy could be augmented by the weighted results in order to make explicit the value of the distributional effects. In this respect, CBA, weighted CBA and cost-impact analysis can be seen as complementary policy analysis tools.

5 SUMMARIES OF THE ARTICLES

The titles of the four articles comprising the thesis are listed in the preface. Following is a brief summary of each.

5.1 Distributional weights in environmental valuation and cost-benefit analysis: theory and practice

In this article, we present the theory of distributional weighting and illustrate how weights can be applied empirically in an international environmental CBA dealing with marine water quality improvements.

Cost-benefit analysis (CBA) is built on the Kaldor-Hicks efficiency criterion, according to which projects that have aggregate positive net benefits are recommended even if those who lose are not compensated for their losses. Two kinds of problems can be identified with the use of the criterion. First, as income tends to affect monetary welfare changes positively, the preferences of those with higher wealth have a larger weight in societal decision making. Second, monetized welfare changes can be thought of as changes in real income, which are more significant for those with a lower initial wealth level. Both problems can be mitigated through distributional weighting. Despite their strong theoretical pedigree, distributional weights have been largely neglected in practical CBAs, one exception being analyses in climate change economics.

The weights are either a straightforward correction for the differences in individuals' income levels (counting average benefits) or a proxy for the social welfare function approach (Adler, 2016), the latter being the more common practice in the rare cases of applied research. It is also possible to use the same monetary value to measure the welfare changes of different income groups, but this is probably not theoretically justified. If the standard approach is applied, that is, CBA is used as a proxy for the social welfare function, one still needs to choose the value of the inequality parameter or to perform a sensitivity analysis to show the effects of different parameter values on the welfare measures.

We show that different weighting schemes can result in different policy recommendations; in some cases, the inclusion of weights can result in a mean WTP that is almost 30 times higher than the unweighted mean WTP. These extremely high multiples occur when the SWF approach is chosen with high inequality parameter values. More conservative results are achieved by choosing to count the average benefits, that is, setting the inequality parameter value to 1. We also show that taking the income distribution within countries into account can change a country's willingness to participate in a water quality improvement program and that the income elasticity of willingness to pay (WTP) is an important indication of the direction of change.

The main conclusions of the article can be summarized as follows:

1) The use of distributional weights can be justified with reference to economic theory. If, however, the decision maker can also adjust tax-transfer schedules and find a Pareto-dominant, politically feasible alternative to the one suggested by a weighted CBA, the Pareto-dominant option should be chosen.

2) The income elasticity of welfare measures is the factor that determines the benefit incidence. If the elasticity is lower/higher than unity, the benefits are regressively/progressively distributed. The inclusion of distributional weights that are calculated separately for each individual increases the benefits if they are regressively distributed.

3) If the average-benefit approach, or logarithmic specification of the SWF approach, is used and weights are calculated separately for each individual, the benefits increase/decrease if they are regressively/progressively distributed.

4) The choice of weighting rule is significant. Region-specific weights, commonly used in climate change economics, do not take intraregional income distribution into account and can correct the results in a direction contrary to that indicated by welfare theory.

Future research should implement distributional weights in the sensitivity analysis of environmental CBAs more extensively and include individual-specific weights in applications of climate change economics. There are also approaches that take the heterogeneity of preferences into account, such as that set out in Fleurbaey et al. (2013), which uses a concept called "equivalent income" for interpersonal utility comparisons. These approaches are interesting but not yet widely applied in economic theory. We have used "income" and "wealth" quite freely as synonyms here, as is common in one-period models in economics. Net wealth would be an appropriate measure of an individual's available budget and thus, in addition to income, future environmental valuation surveys should incorporate questions of wealth to improve the construction of distributional weights. Lastly, we use observed WTP-income pairs. However, average and total WTP are usually estimated from an estimated WTP function. It is a question for future research to determine whether distributional weights should also be derived from modeled WTP-income pairs.

5.2 Overadaptation to climate change? The case of the Finnish Electricity Market Act 2013

In this article, we provide a definition of over-adaptation in disaster risk reduction and climate change adaptation investments. We present an illustrative case in which, as opposed to maladaptation, the response to extreme weather risk is aligned with the goals of climate change adaptation yet implemented over the economically efficient proportion. We undertake a social cost-benefit analysis of the 2013 Finnish Electricity Market Act, which was partially a reaction to long, storm-induced electricity blackouts experienced after 2000. The Act imposes strict requirements on electricity distribution companies regarding permissible blackout durations and requires the companies to make sizable investments amounting to billions of euros.

As a benefit, we quantify the avoided cost of the blackouts for households and producers. Our results derived from Monte-Carlo simulations show that for urban areas the net expected value is positive. However, in rural areas, less strict requirements might have been economically more efficient.

Our results indicate that distributional impacts and the correspondence between those who benefit and those who pay the costs should be taken into account in climate change adaptation and disaster risk reduction policies that require large-scale investments. We also note that the population affected by a disaster may not accept disaster risk reduction and climate change adaptation that is successful with respect to regulation and implementation. This applies particularly when societal and individual preferences do not match.

Over-adaptation to the impacts of extreme weather and climate change is rarely discussed in the literature. The literature is rich in examples where climate change adaptation and disaster risk reduction measures are reported to be economically efficient, whereas counter-examples are rare. However, over-adaptation is likely to produce projects that are neither highly negative (since the measure is desirable to some extent) or highly positive (since, by definition, the measure is overprovisioned). Previous studies show that such results are rarely reported in the scientific literature, as they are not considered as interesting as strikingly positive or negative results. We can only hypothesize that this might also be a tendency in the case of research on risk reduction and climate change adaptation policies and measures.

Following are the main findings of the article:

1) Over-adaptation, defined as a beneficial disaster risk reduction or climate change adaptation project or measure supplied at a higher than economically optimal quantity, is a relevant concept in climate adaptation and disaster risk reduction literature. However, the literature lacks such research on such cases;

2) The policy might have been an overreaction to an existing problem: It seems that at some quantity (urban requirements), net present value is strictly positive, whereas at another level of service provision (rural requirements), the net present value is negative;

3) Other economic criteria, such as distributional effects and the correspondence between those who benefit and those who pay the costs, should be considered in disaster risk reduction and climate change adaptation policies requiring large-scale investments;

4) With these effects taken into account, the policy in question turns out to be more problematic. The correspondence between those who pay and those who obtain the benefits is dependent on the spatial characteristics of the electricity grid. In some cases, the urban population ends up paying the bill for the rural customers (correspondence principle violated), and in some cases a low-income, rural population might end up paying a much higher price than their WTP indicates; that is, the distributional impacts are highly negative.

5) Our case also shows that when assessing the success of public regulation and measures aiming at reducing the risk of extreme weather events and climate change, public opinion and potential, perceived negative effects on the public should be considered. The population affected by the impacts may not accept the implementation of otherwise effective disaster risk reduction and adaptation measures. This applies particularly when there is a potential mismatch between societal and individual preferences. Furthermore, the WTP of the people affected should be carefully evaluated prior to a policy change, as the WTP obtained in surveys may turn out to be different from the WTP of the affected population.

5.3 Innovations in weather services as a crucial building block for climate change adaptation in road transport

In this article, we evaluate how foreseen innovations in weather services could reduce weather sensitivity and thereby reduce the negative effects of climate change in the road transport sector. The sector is facing rising uncertainties in planning and operations due changes in weather variability and extreme events, trends caused by climate change. However, because of the high level of uncertainty related to the future climate, adaptation measures should be robust as this maintains the option value of the portfolio of measures.

The study is based on a theoretical framework for climate change adaptation and valuation of weather and climate services using Weather Service Chain Analysis, an approach elaborated in the article. We apply the framework to analyze the road transport sector with special emphasis on drivers' decision making before and during a trip. We show that improved weather information, including more accurate weather forecasts, new applications, and improved information dissemination channels, can decrease the vulnerability of the mode of road transport to projected shifts in extreme weather patterns due to climate change. A literature review and user survey conducted as part of the study indicate that the expected changes in weather variation and in extreme weather patterns are the main threats that climate change poses to the transport sector in Europe. However, keeping in mind both the high level of uncertainty in climate predictions and the fact that users of modes of transport mainly react to adverse weather at the operational or tactical levels, costly anticipatory alterations in transport infrastructure entails significant regret costs. Consequently, an important part of climate change adaptation in the transport sector will occur through processes that produce learning benefits enabling better operational- and tactical-level decision making in adverse weather situations. This in turn has the promise of better-scaled transitional adaptation investments later on. Innovation in weather services is a crucial building block in this learning process.

It is clear that the potential value of weather service provision has not been fully realized. Investments in research and development, leading to innovations, were shown to be beneficial in increasing avoided accident costs. For example, innovations bringing improvements in the weather service chain will significantly decrease the vulnerability of road transport to extreme weather events and reduce weather-related costs and thus play a key role in the sector's climate change adaptation process. Overall, innovations enhance automatic adaptation capabilities, which extends the coping range of the road transport system. The benefits of innovations are naturally dependent on the overall development of society and the climate. The article also serves as an example of how information on weather events, a type of public good, can be evaluated in economic terms.

The first limitation of the analysis presented in this article is the gap in research knowledge on the impacts of climate change on the transport sector, as a result of which we lack estimates of the accident rates and costs in the climate and society of the future. Paradoxically, this limitation stems from the same reasons as the suggested need for the robust, no-regret adaptation options. Another limitation of the analysis is the qualitative nature of Weather Service Chain Analysis and the consequent need to occasionally estimate the quantitative level of each step based on qualitative data only. Nevertheless, the analysis is a comprehensive tool as it makes it possible to assess the full weather service provision chain from the generation of the information to the end user's response and resulting benefits. The development of Weather Service Chain Analysis is progressing toward creating quantitative indicators with objective criteria to assess the current status and the development needs of each step. With these improvements, the approach could be used in multiple contexts and provide more objective estimates of the benefits and development needs. Among other things, the benefit estimates could be used in CBAs of selected investments.

5.4 Green Roof Cost Benefit Analysis: Special Emphasis on Scenic Benefits

In this fourth article, we present a green roof CBA. Green roofs are roofs which are partially or completely covered by vegetation. We discuss the benefits and costs of light self-sustaining vegetated roofs. The benefits of the ecosystem services (ES) provided by green roofs can be classified into private and public benefits. We apply the selected valuation methods, such as avoided cost and hedonic pricing, in Helsinki, Finland, and proceed to explain how the results can be transferred to other urban locations. Past research and this study show that private benefits are usually not high enough to justify what is an expensive investment for a private decision maker. However, when the public benefits are added to the private, in most cases the social benefits are higher than the costs of green roofs.

Past research has quantified most types of the benefits associated with green roofs, exceptions being scenic and biodiversity benefits. Scenic benefits denote the intangible benefits that people derive from the presence of green space, with these including at least aesthetic and psychological benefits. In this article, special emphasis is placed on the valuation of scenic benefits, which are among the most challenging benefits to valuate in monetary terms. We employ hedonic pricing theory, implemented via spatial regression models, as well as green roof implementation scenarios in order to estimate the aggregate willingness-to-pay for a 'unit' of green roof. The results show that scenic benefits can be a significant attribute in cost-benefit calculations; however, the amount of benefits strongly depends on the design of the green roofs in a given case.

The main conclusions of green roof cost-benefit analysis in Helsinki are:

1) As the reviewed literature suggests, the private benefits are usually not high enough to cover the current level of additional private costs. In Helsinki, even in the low-cost/high-benefit scenario the private net present value is negative. However, in some circumstances, in warm climates, the cooling energy savings increase the private net present value to positive levels. The most important parameters determining the private benefits are the following: the cost of the reference roof, with a higher reference roof price increasing the benefits; the temperature profile of the location, with higher temperatures increasing the benefits; the price of energy, with higher energy prices increasing the benefits; and the building code governing the roof, with a higher coefficient of heat loss increasing the benefits.

2) When adding up private and public benefits, benefits surpass costs in most of the cases, especially if a higher implementation rate lowers costs. The factors that have a positive effect on the public benefits, which are at a relatively low level in Helsinki, are the average annual precipitation and frequency of extreme rainfall, the maintenance backlog of the current sewer system, and the concentration of particulate matter. As the cost of green roofs is high in Helsinki and Finland at large, the social net present value in most other cities of similar size or larger in other countries can be expected to be higher than that reported in this study.

3) Scenic benefits have the potential to be a significant factor in green roof CBA. For example, the increase in property values in buildings within 30 meters of a green roof were estimated to be between 0 percent and 1.2 percent. Helsinki is a comparatively green city, meaning that scenic benefits are likely to be higher in many other cities as they have less vegetation cover. Compared to other benefits, scenic benefits represent 13 percent of the total benefits of the high-estimate case for social benefits, or approximately 13 percent of the expected value of the benefits.

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7 Mathematical Appendix

A1. Proof of complementary condition, section 3.2.

The simplest way to show this is to study equations [23] and [24]. First, we want to explore the case where EV>CV. Thus, we write:

$$e\left(q_{0,}u_1\right) - e(q_1, u_1) > e\left(q_{0,}u_0\right) - e(q_1, u_0) \quad \text{[A1]}$$

Rearranging the equation, we get:

$$e\left(q_{0,}u_1\right) - e(q_0, u_0) > e\left(q_{1,}u_1\right) - e(q_1, u_0) \quad \text{[A2]}$$

Since $q_0 < q_{1,}$, and $u_1 > u_0$, for the identity to hold, the expenditure function must have strictly decreasing differences in (q, u) such that the smaller q is, the greater the increase needed in the expenditure to attain a higher level of utility.

$$\frac{\partial e(q,u)}{\partial - q \partial u} > 0 \quad \text{[A3]}$$

Next, consider two utility levels, $u_H(p, q_0, y_h)$ and $u_L(p, q_0, y_{l)}$, in which u_H corresponds to the utility level attained with prices p, environmental quality q_0 and high income y_h, and u_L corresponds to the utility level attained with p, environmental quality q_0 and low income y_L. We want to explore when the monetary welfare change from q_0 to q_1 is higher for the wealthier individual. We apply it to CV in equation [23], but it could also be applied to EV. We write:

$$e\left(q_{0,}u_H\right) - e(q_1, u_H) > e\left(q_{0,}u_L\right) - e(q_1, u_L) \quad \text{[A4]}$$

Rearranging this we get:

$$e\left(q_{0,}u_H\right) - e(q_0, u_L) > e\left(q_{1,}u_H\right) - e(q_1, u_L) \quad \text{[A5]}$$

This is exactly the same condition as equation [A3] since $q_0 < q_{1,}$, and $u_H > u_L$. We want to show that this now holds for the wealth effect such that $e(q, u(y))$ has strictly decreasing differences in (q, y), whereby the smaller the q is, the greater the needed increase in the expenditure is to attain the higher level of utility, which itself is a function of reference income. If the function $e(q, u(y))$ is continuous, it is again both a necessary and sufficient condition that:

$$\frac{\partial e}{\partial - q \partial u \frac{du}{dy}} > 0 \quad \text{[A6]}$$

Since $\frac{du}{dy} > 0$, this always reduces to:

$$\frac{\partial e}{\partial - q \partial u} > 0 \qquad [A7]$$

A2. Deriving the income elasticity of virtual price.

$$\eta(p_v, y) = \frac{\partial p_v(p, q_0, y)}{\partial y}\frac{y}{p_v} \qquad [A8]$$

Equation [A8] can be used to derive to express the income elasticity of virtual price in terms of income elasticities of demand by taking the partial derivate of equation 36 with income. For one non-market good, the analysis goes as follows (Haneman, 1991):

$$0 = \frac{\partial q_v}{\partial p_v}\frac{\partial p_v}{\partial y} + \frac{\partial q_v}{\partial y}\left(1 + \frac{\partial p_v}{\partial y}q_0\right) \qquad [A9]$$

$$\frac{\partial p_v}{\partial y}\left(\frac{\partial q_v}{\partial y}q_0 + \frac{\partial q_v}{\partial p_v}\right) = -\frac{\partial q_v}{\partial y} \qquad [A10]$$

$$\frac{\partial p_v}{\partial y} = \frac{-\frac{\partial q_v}{\partial y}}{\left(\frac{\partial q_v}{\partial y}q_0 + \frac{\partial q_v}{\partial p_v}\right)} \qquad [A11]$$

By Slutsky decomposition, the denominator $\left(\frac{\partial q_v}{\partial y}q_0 + \frac{\partial q_v}{\partial p_v}\right)$ can be expressed as the Hicksian own price derivate $h^q_{p_v}(p, p_{v,} v(p, q_0, y)$, which is always negative. Thus, in the case of a normal good, $-\frac{\partial q_v}{\partial y}$ is negative or $\frac{\partial q_v}{\partial y}$ is positive, in which case the virtual price is increasing with income.

Equation [A11] can also be converted into elasticity form:

$$\eta(p_v, y) = \frac{\partial p_v(p, q_0, y)}{\partial y}\frac{y + p_v q}{p_v} = -\frac{\eta(\partial q_v, y)(1-\alpha)}{\varepsilon} \qquad [A12]$$

where $\eta(q_v, y)$ is the elasticity of the ordinary demand function for q, $\alpha = \frac{p_v q_v(\boldsymbol{p}, p_v(\boldsymbol{p}, q_0, y)}{y + p_v q}$ is the budget share of q related to virtual income, and $\varepsilon = \frac{p_v h^q_{p_v}(p, p_{v,} v(p, q_0, y)}{h^q(p, p_{v,} v(p, q_0, y)}$ is the own-price elasticity of the Hicksian demand function. Following Haneman (1991) ε can be written by $\varepsilon = -\sigma_0(1 - \alpha)$, where σ_0 is the aggregate Allen-Uzawa elasticity of substitution between q and other goods and $\eta(p_v, y)$ can be written as:

$$\eta(p_v, y) = \frac{\eta(q_v, y)}{\sigma_0} \qquad [A13]$$

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Ecological Economics, 56:6, 1045-1053

https://doi.org/10.1016/j.ecolecon.2018.04.021

Ecological Economics 150 (2018) 217–228

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Distributional Weights in Environmental Valuation and Cost-benefit Analysis: Theory and Practice

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ARTICLE INFO

Keywords:
Cost-benefit analysis
Environmental valuation
Distributional weighting
Willingness to pay

ABSTRACT

Cost-benefit analysis (CBA) is built on the Kaldor-Hicks efficiency criterion whereby projects that have aggregate positive net benefits are recommended even if those who lose are not compensated for their losses. Two kinds of problems can be identified with the use of the criterion. First, as income tends to affect monetary welfare changes positively, the preferences of those with higher wealth have a larger weight in societal decision-making. Second, monetary welfare changes can be thought of as changes in real income, which matter more for those with a lower initial wealth level. Both problems can be mitigated with distributional weighting. Despite their strong theoretical pedigree, distributional weights have been largely neglected in practical CBAs, one exception being analyses in climate change economics. We present the theory of distributional weighting and illustrate how weights can be applied empirically in an international environmental CBA that deals with marine water quality improvements. We show that different weighting schemes can result in different policy recommendations. We also show that taking the income distribution within countries into account can change a country's willingness to participate in the water quality improvement program and that the income elasticity of willingness to pay (WTP) is an important indication of the direction of change.

1. Introduction

Economic valuation of environmental goods and cost-benefit analysis (CBA) can form a valuable part of the information base for decision-making (Freeman et al., 2014; Bergstrom and Randall, 2016). The CBA is built on the Kaldor-Hicks efficiency criterion (e.g. Boadway, 2006; Coleman, 1980; Adler and Posner, 1999), which allows a favorable project to have both winners and losers but with the winners compensating the losers and still being better off. If such compensation is paid, the project turns out to be a Pareto Improvement, but no actual compensation is required for Kaldor-Hicks efficiency (Coleman, 1980).

To determine Kaldor-Hicks efficiency in a CBA, the total benefits and costs are typically measured in money, making income the numeraire (Dreze, 1998). The two relevant welfare measures, compensating variation (CV) and equivalent variation (EV), measure the monetary equivalent of the effect that change in the environmental good would have on the individuals' welfare. When either CV or EV is aggregated over individuals, a positive number indicates that the project should be recommended, as the monetary gains are higher than the monetary costs. It is this "aggregate benefit criterion" (ABC) that forms the principal basis for cost-benefit analysis and modern welfare economics (Dreze, 1998; Freeman et al., 2014).

Both theoretical (e.g. Boadway, 1974; Scitovsky, 1941; Blackorby and Donaldson, 1990) and ethical problems (e.g. Mishan, 1982; Sen, 2000; Dreze, 1998; Nyborg, 2014) have been identified in using the ABC as a decision rule. We concentrate on the problem of using income as a numeraire without adjusting it to account for differences in the *social marginal utility of money*. From their first introductory course, economists are taught the law of diminishing marginal utility as a golden rule, only to see it forgotten later when applying the ABC. Without adjusting or "weighting" monetary welfare changes to take into account the social marginal utility of money, CBA is systematically favorable to those who value money the least relative to alternative numeraires (Brekke, 1997; Dreze, 1998; Boadway, 2006). The reason for this is that, due to the diminishing marginal utility of money, the rich are usually willing to give up more of their income for a given (equally desirable) change and thus their opinion matters more in the social decision-making. In more technical terms, CBA is not symmetric among agents, as it is not irrelevant how a given vector of preferences is distributed among individuals: For example, if we change preferences

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https://doi.org/10.1016/j.ecolecon.2018.04.021
Received 15 December 2017; Received in revised form 12 April 2018; Accepted 14 April 2018

such that a wealthy individual who initially preferred a golf course to a public park now prefers a public park to a golf course, and a poor individual reverses his or her preferences from a park to a golf course, it may very well be that the ranking of alternatives based on the ABC also changes.

As Dreze (1998) points out, in economic theory the need for adjustments or weights for individual welfare changes is well known but largely forgotten in practice. Many modern textbooks in environmental valuation (e.g. Freeman et al., 2014) focus very little on the use of distributional weights, while some (e.g. Boardman et al., 2006) discuss them briefly but nevertheless base most of the theory on the ABC. Organizations such as the World Bank abandoned the use of weights decades ago, but environmental policy analysts have recently shown renewed interest in them, with Hallegatte et al. (2016) applying them in a report on the poverty induced by disaster risks. On a national level, the UK government officially recommends using distributional weights in CBA (HM Treasury, 2003). It is also rare to find distributional weights included in the analyses in practical valuation studies (Adler, 2013; Nyborg, 2014). An exception is climate change economics (e.g. Nordhaus and Boyer, 2000; Fankhauser et al., 1997; Tol, 2005; Shiell, 2003; Anthoff et al., 2009; Dennig et al., 2016; Anthoff and Emmerling, 2016), where weights have been used to account for the different income levels between countries, mainly developed and developing countries. The results have shown that the order of magnitude of climate change damages can change by two if equity weights are used, making CBA results extremely sensitive to weighting (Anthoff et al., 2009). It is our hypothesis that similar results could be obtained in CBAs of other environmental goods.

This paper contributes to the limited empirical literature on the effect of using distributional weights in environmental valuation studies and CBA. We 1) provide a connection between the income effect and distributional issues, 2) compare different weighting schemes both theoretically and empirically, 3) show how the weights could be incorporated in a valuation study in practice, and 4) demonstrate that the results are sensitive not only to whether the weights are applied or not, but also to the choice of weighting rule and spatial resolution. In the empirical application, we use data from a contingent valuation study conducted in nine countries on people's willingness to pay for improved water quality and employ a range of weights to study the effects on the results of the CBA, much as a sensitivity analysis would. This approach has been advocated by at least Hanley (2001), Johansson-Stenman (2005) and Boardman et al. (2006) and applied in practice with regional weights for the costs of climate change damages by Fankhauser et al. (1997), Tol (2005) and Anthoff et al. (Anthoff et al., 2009 & Anthoff and Emmerling, 2016), and for natural disasters by Hallegatte et al. (2016).

The paper is organized as follows. Section 2 gives a theoretical overview of how income affects measured monetary welfare changes and the benefit incidence of a project. In Section 3 we then go on to discuss how these changes can be adjusted to take into account the social marginal utility of money and what the theoretical arguments for or against using weights are. In Section 4, we describe the data, and in Section 5 we test how the different adjustment mechanisms, or weightings, affect estimated environmental values and the results of a CBA. Section 6 provides a discussion of the results and Section 7 our conclusions.

2. The Effect of Income on Welfare Changes

In this section, we introduce the relevant welfare measures and review the theory of how these are affected by income. We also show that the benefit incidence ("who gets the benefits") is crucially dependent on the income elasticity of the welfare measures, for it measures how unevenly the benefits are distributed among different income groups. Last, we present empirical estimates for the income elasticity of welfare measures. Income elasticity is connected to the distributional weights and their impacts on CBA results in Section 3 and to the empirical results in Section 5.

The two relevant concepts for the Kaldor-Hicks efficiency test are compensating variation (CV) and equivalent variation (EV). For a gain in environmental quality/quantity (from q_0 to q_1), CV measures the willingness to pay (WTP) to obtain the change, and EV the willingness to accept compensation (WTA) to forego the change. CV and EV are defined with the expenditure function $e(q,u)$, where u_0 stands for the initial utility before the environmental quality/quantity change and u_1 stands for the utility after the change:

$$CV = e(q_0, u_0) - e(q_1, u_0) \tag{1}$$

$$EV = e(q_0, u_1) - e(q_1, u_1) \tag{2}$$

How the outcome of a CBA is affected by individuals' income differences is thus crucially dependent on how income affects CV and EV, as the more sensitive the welfare measures are to changes in income, the more the CBA gives weight to the preferences of wealthier people. Accordingly, we need to have a measure for the magnitude of the income effect, relate it to the benefit incidence, and find ways to correct the results to account for these effects.

2.1. Benefit Incidence

Benefit incidence can be linked to the concepts in Eqs. (1) and (2) as follows (Ebert, 2003; Lamber, 2001):

If the benefit b, defined as the welfare change (either CV or EV) divided by income y $b(\boldsymbol{p},q,y) = B(\boldsymbol{p},q,y)/y$, increases (decreases) with income ($\boldsymbol{p}$ is the price vector of all commodities) such that $\frac{\partial b(p,q,y)}{\partial y} > 0$ (< 0), then the benefits are distributed progressively (regressively). From direct partial differentiation of $B(\boldsymbol{p},q,y)/y$ with respect to income y, and using WTP as the measure of benefits ($B = WTP$), we obtain the main result presented in Ebert (2003):

$$\frac{\partial WTP(\boldsymbol{p},q,y)/y}{\partial y} = \frac{\partial WTP}{\partial y}\frac{1}{y} - \frac{WTP}{y^2} = \frac{WTP}{y^2}(\eta(WTP,y) - 1) \tag{3}$$

where $\eta(WTP,y)$ is the income elasticity of WTP.

The income elasticity of WTP ($\eta(WTP,y)$ can then be used in defining the benefit incidence as follows:

$$if\ \eta(WTP,y) > 1,\ \text{then}\ \frac{\frac{\partial WTP(\boldsymbol{p},q,y)}{y}}{\partial y} > 0;\ \text{the benefits are distributed progressively.} \tag{4}$$

$$if\ \eta(WTP,y) < 1,\ \text{then}\ \frac{\partial WTP(\boldsymbol{p},q,y)/y}{\partial y} < 0;\ \text{the benefits are distributed regressively.} \tag{5}$$

$$if\ \eta(WTP,y) = 1,\ \text{then}\ \frac{\partial WTP(\boldsymbol{p},q,y)/y}{\partial y} = 0;\ \text{the benefits are distributed proportionally.} \tag{6}$$

The income effect and its measure, the income elasticity of WTP, are the crucial factors determining 1) who has standing in a CBA and 2) who obtains the benefits. Let us take an example where the income elasticity of WTP for a given project is very close to 0 and the benefits are regressively distributed. Clearly, in such a case the good is mainly enjoyed by lower-income groups, who have a limited budget to express their preferences, and the use of distributional weights should increase the aggregate benefits relative to a project with a higher income elasticity of WTP.

2.2. Income Elasticity of WTP

The two main results related to the income elasticity of WTP, obtained by Haneman (1991) and Flores and Carson (1997), respectively, are both derived from the economics of rationed goods. For present purposes, the analysis can be simplified in terms of the following question: If the environmental good were a market good, what price for that good and what income would induce a person to buy exactly the available amount (q_0) and yet still enable him or her to buy the same basket of market goods he or she chose in the market? The answers to this question are termed the *virtual price* p_v and the *virtual income* $y_v = y + p_v q_0$. Virtual price is an important concept as it can be shown to equal the marginal WTP at q_0 (Flores and Carson, 1997) and its derivative with respect to income has the same sign as the derivative of WTP with respect to income. The income elasticity of WTP is a weighted average of the income elasticities of the virtual prices over the change from q_0 to q_1, and thus a slightly more complex equation (Flores and Carson, 1997; Ebert, 2003).

By the definition of virtual price and virtual income, we can write an identity which simply states that the current quantity of environmental good q_0 would have been bought by the decision-maker if it were available in the market, if its price were the virtual price p_v and the budget available were the virtual income $y + p_v q_0$ (Haneman, 1991):

$$q_0 = \dot{q}(\boldsymbol{p}, p_v(\boldsymbol{p}, q_0, y), y + p_v q_0) \tag{7}$$

Using total derivation of Eq. (7) with respect to income and with some basic algebra, Haneman (1991) arrived at the following result, which makes it possible to decompose the derivate of a virtual price with respect to income into concepts familiar from consumer theory:

$$\frac{\partial p_v}{\partial y} = \frac{-\frac{\partial \dot{q}}{\partial y}}{\left(\frac{\partial \dot{q}}{\partial y} q_0 + \frac{\partial \dot{q}}{\partial p_v}\right)} \tag{8}$$

By Slutsky decomposition, the denominator $\left(\frac{\partial \dot{q}}{\partial y} q_0 + \frac{\partial \dot{q}}{\partial p_v}\right)$ can be expressed as the Hicksian own price derivate $h_{p_v}{}^q(p, p_v, v(p, q_0, y))$, which is always negative. Thus, in the case of a normal good, the derivate of the ordinary demand function $\frac{\partial \dot{q}}{\partial y}$ is positive and the virtual price is increasing with income. This is intuitive: if the environmental good is a normal good, we know that the WTP is increasing with income. Haneman (1991) converted Eq. (8) into an elasticity form:

$$\eta(p_v, y) = \frac{\eta(\dot{q}, y)}{\sigma_0} \tag{9}$$

where $\eta(p_v, y)$ is the income elasticity of virtual price, $\eta(\dot{q}, y)$ is the ordinary income elasticity of demand and σ_0 is the aggregate Allen-Uzawa elasticity of substitution between q and other goods.

Thus, the income elasticity of the virtual price is dependent on the ordinary income elasticity of demand and the substitutability between the environmental good and market goods. If the substitutability is perfect, then $\sigma_0 = \infty$ and the income elasticity is zero. Note that the elasticity of the virtual price can also be low or close to zero with high income elasticity of demand (the case of a luxury good in the ordinary sense), and even when the good in question has higher substitutability with the market goods. A good that would be normally classified as a luxury good (the income elasticity of demand is above 1) may become classified as a good that mainly benefits the poor (Ebert, 2003), as the income elasticity of virtual price may be < 1, see Eqs. (4)–(6).

Using a similar analysis but treating Eq. (7) as a vector of public goods and differentiating each element with respect to income, Flores and Carson (1997) show that this kind of logic no longer applies in the (more realistic) case of multiple environmental (or otherwise rationed) goods. Rather, the elasticities of the virtual prices in the case of two public goods can be expressed as:

$$\begin{pmatrix} \eta_1(p_v, y) \\ \eta_2(p_v, y) \end{pmatrix} = -\begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix}^{-1} \begin{pmatrix} \eta_1(\dot{q}, y) \\ \eta_2(\dot{q}, y) \end{pmatrix} S_x^v \tag{10}$$

where σ_{ij} is the Hicksian cross-price substitution elasticity of demand for q_i and q_j and $S_x{}^v$ is the budget share devoted to market goods, specified as $S_x^v = \frac{y}{y + p_v q}$. The income elasticity of marginal WTP then involves income elasticities of demand for all rationed goods, inverted cross-price demand substitution elasticities and the share of virtual expenditure devoted to market goods. The intuition of Eq. (8) does not hold anymore, as Flores and Carson (1997) show that even an inferior good (measured by negative income elasticity of demand) can have an income elasticity of WTP or virtual price > 1 and be categorized as a progressively distributed good in the sense of Section 2.1. Thus, it is not always clear based on intuition alone in which direction aggregate or mean estimates should be corrected.

2.3. Empirical Estimates of the Income Elasticity of WTP

The theory presented thus far does not in itself allow us to establish whether environmental goods are inferior, normal or luxury goods, or which population group they benefit the most. Fortunately, many studies directly measure the income elasticity of WTP for environmental goods. Income elasticity is usually estimated from a WTP function that attempts to explain the variation in WTP by regressing WTP on explanatory variables, including personal income. Using such a function, the income elasticity of WTP can be estimated as: $\frac{\partial WTP}{\partial y}\frac{y}{WTP} = \frac{\partial(lnWTP)}{\partial(lny)}$. A log-log specification of the relationship between WTP and income yields a coefficient value that can be interpreted as an estimate of the income elasticity of WTP (Jacobsen and Hanley, 2009). This approach is applied in Section 5 of this article.

Hökby and Söderqvist (2003) estimated $\eta(WTP, y)$ from a set of 40 contingent valuation studies in Sweden, of which 29 provided enough information for the calculation of $\eta(WTP, y)$. They reported income elasticities of WTP ranging from -0.71 to 2.83. Only one of the estimated elasticities was negative, and only four greater than unity. The mean $\eta(WTP, y)$ was 0.68, and median 0.46. In a meta-analysis of environmental contingent valuation studies, Kristöm and Riera (1996) also found that income elasticity of WTP tends to be persistently lower than one. Even more evidence was gathered by Jacobsen and Hanley (2009), who analyzed > 140 WTP studies throughout the world. They concluded that on average $\eta(WTP, y)$ was 0.38 in those studies that provided enough information to calculate the income elasticity of WTP. In a meta-analysis of WTP for improvements of surface water quality, Tyllianakis and Skyrus (2016) found a mean $\eta(WTP, y)$ close to 1, with a range from 0.6 to as high as 1.7. Barbier et al. (2015) showed that income elasticity is not constant across income groups, concluding that for lower-income groups the income elasticity of WTP is between 0.1 and 0.2, and for higher-income groups between 0.6 and 0.7. Overall, the evidence suggests that environmental benefits are regressively distributed.

3. Theory and Practical Determination of Distributional Weights

3.1. Why Use Distributional Weighting?

The income effect described in Section 2 causes a potential problem in CBA in that the use of income as the numeraire gives a higher weight to the preferences of people with low marginal utility of money (i.e. a higher income level). The question is who has standing in a CBA (Trumbull, 1990; Adler and Posner, 1999; Dreze, 1998; Boardman et al., 2006). Projects that the poor prefer relatively more than the rich – projects with an income elasticity of WTP < 1 – are discriminated against compared to projects with income elasticity above 1. Numerous stylized examples can be found in the literature (e.g. Dreze, 1998; Johansson-Stenman, 2005).

In addition, a dollar gain should count more for the poor than for the rich if the marginal utility of income is decreasing, as is often assumed and as has been demonstrated empirically measured (e.g. Layard et al., 2008; Nyborg, 2014). Furthermore, it can be argued that an increase in utility should count more if the initial level of utility is low. In other words, a moral judgement prevails to the effect that the social welfare function (SWF) should be strictly concave in individuals' utilities (e.g. Adler, 2013).

Both of these problems can be addressed with equity or distributional weights designed to give a higher weight to the (monetary) welfare changes of individuals with lower incomes.

3.2. Arguments Against Weighting

It is not self-evident that any kinds of distributional weights should be used in CBAs, and many economists argue against them. It is rare to find a recent cost-benefit analysis that has applied distributional weights, one exception being climate change-related CBAs. Adler (2013) points out that despite their theoretical pedigree, distributional weights have hardly ever been used by CBA practitioners, at least in the U.S. As noted in the introduction, the World Bank, which abandoned weights decades ago, has recently begun using them again.

Political, practical and theoretical explanations have been put forward for the neglect of distributional weights. The practical reasons, pointed out by Boadway (2006) and Dreze (1998) among others, are that it is more convenient to do a CBA without weights and that sometimes the data gathered do not allow the use of weights, for example in cases where individuals' incomes are not paired with their WTPs. The political reasons (e.g. Dreze, 1998) are that decision-makers may be siding with the rich or may hold a normative view that individuals' marginal social utility of money is equal irrespective of their income.

The theoretical reasons, many of which can be traced back to Harberger (1978) and Hylland and Zeckhauser (1979), can be classified into three groups (Boadway, 2006; Adler, 2013): 1) The focus of a CBA should be on efficiency and distributional impacts should be taken care of with other instruments; 2) the Kaldor-Hicks compensation principle states that income could (hypothetically) be distributed in a Pareto-efficient way if the ABC is applied; and 3) implementing many projects evens out individuals' gains and losses in the long term such that there are no winners and losers. We go through each of these arguments briefly in what follows.

Some theoretical papers present reasoning that supports the first argument, that is, that under some specific conditions on individual utility functions, the overall economic pie is larger if distributional concerns are dealt with solely through income taxation (e.g. Harberger, 1978; Hylland and Zeckhauser, 1979; Kaplow, 1996 and 2008). This separation of efficiency and distributional considerations has been shown to be invalid, with two exceptions (Johansson-Stenman, 2005; Boadway, 2016):

1) where the economy is fully efficient and there are no distortions and
2) where the distributional problems can be addressed through an optimal tax system with three options:
   a. The government is able to raise revenues using an optimal set of taxes that take into account equity concerns via the SWF
   b. The traditional unweighted Samuelson (1954) should apply such that the summed marginal utilities (in income units) should equal the marginal costs if optimal nonlinear taxes are in place, preferences for public and private goods are independent of the supply of labor and these preferences are weakly separable (Boadway and Keen, 1993; Johansson-Stenman, 2005)
   c. Preferences are weakly separable and non-optimal income taxes are suitably adjusted simultaneously with the decision on the supply of public goods (Kaplow, 1996 and 2006).

The separability of preferences (conditions b and c under item 2 above is crucial because of the government's ability to change the tax schedule without distorting labor supply decisions (Boadway and Keen, 1993; Johansson-Stenman, 2005). As noted in these two studies, the debate is mainly a theoretical one if the public good is financed from a pre-collected government budget and results in no changes in the tax schedule, as is usually the case with new, small projects. Even if distributional weights are not taken into account in the choice of project and one believes that the assumption of separability in leisure is a valid one, weights should be included in the analysis when choosing the tax-transfer system (Adler, 2013; Boadway, 2006). Moreover, an expanded schedule of policy options should be considered, including ones with feasible tax-transfer schedules (Adler, 2013).

The second theoretical argument, based on the compensation principle, is mainly a hypothetical one: If the compensation due those who incur losses from the project is paid, the project is Pareto efficient. Without the compensation, not much can be said about its efficiency. The earlier discussion of separability and optimal taxes essentially covers the question whether the government can affect this compensation through taxes. Other mechanisms are hard to imagine, although discussion of payments for ecosystem services points in this direction.

The third argument, regarding multiple projects, claims that if many policies with positive net benefits are undertaken over time, individuals' gains and losses will even out eventually such that there are no winners and losers – only winners. This argument can be traced to Polinsky (1972) and in a slightly cruder from to Hicks (1941). Polinsky (1972) supported ABC-criterion with probabilistic arguments and called the efficiency criterion *multi-change hypothetical compensation criteria*. Without the corrections – kind of welfare weights that were in fact discussed in the remarks section of Polinsky (1972) - to account for differences between different income groups, the argument relies on there being statistical independence between the beneficiaries of different projects. The discussion presented above has already established that this assumption is invalid in most cases, as the ABC-criterion is not symmetric between preferences and the income distribution affects ranking of different alternatives, making the beneficiaries between projects partly correlated.

The theoretical debate can be summarized as follows:

1) In the case of projects that result in no changes to the tax schedule, distributional weights should be used (Johansson-Stenman, 2005).
2) If the decision-maker can simultaneously change the tax-transfer schedule, a menu of policy options should be analyzed, including combinations with feasible tax schedules. However, the analyses should use weights and adjust for the distortionary effects of taxes (Adler, 2013).
3) The decision not to use weights is itself a decision. It gives equal weight to all individuals and if one believes that the assumption of diminishing marginal utility of money is true, one implicitly gives higher weight to the utility changes of people with a high initial level of income (Nyborg, 2014).

3.3. Weights Based on Social Welfare Functions

The starting point in welfare theory is usually the Social Welfare Function (SWF), first developed by Bergson (1938) and Samuelson (1947). Rather than assigning an equal weight to each individual's welfare change in monetary terms, the SWF approach compares the marginal social benefits of money between individuals and aggregates the monetary welfare changes on that basis (Fankhauser et al., 1997; Boadway, 2006; Johansson-Stenman, 2005). The weights are derived using an SWF that is written in an additive separable form, where u_i is the utility of agent i:

$$W(u_1,\dots,u_n) = \sum_i w(u_i) \tag{11}$$

Next, as a further simplification, it is common to assume that the SWF takes the constant elasticity form (also known as the Atkinson form) in individuals' utilities (Boadway, 2006; Johansson-Stenman, 2005; Adler, 2013):

$$W(u_1,\dots,u_n) = \sum_i w(u_i) = \sum_i u_i^{1-\rho}/(1-\rho) \tag{12}$$

where $\rho = -\frac{uw''(u)}{w'(u)}$ represents the coefficient of aversion to inequality, analogous to the coefficient of relative risk aversion in the theory of choice under uncertainty. Note that if ρ is 0, the above equation becomes a utilitarian SWF in the sense that a change in utility counts equally for all individuals. If ρ = 1, the above expression is not defined, and an SWF with logarithms of each individual's utilities is applied instead. We turn in to this special case later.

The next step needed is to explore how the SWF reacts to changes in the income y of individuals by defining how individuals' utility is connected to their income. It is common to assume a constant elasticity function here as well, in this case a form (CRRA) of the von Neumann-Morgenstern utility function (VNM function). Thus,

$$u(y) = \frac{y^{1-\alpha}}{(1-\alpha)} \tag{13}$$

By combining Eqs. (12) and (13) one obtains:

$$w(u_i(y_i)) = w(y_i) = y_i^{(1-\alpha)(1-\rho)} * (1-\alpha)^{(\rho-1)}/(1-\rho) \tag{14}$$

and SWF becomes:

$$W(y_1,\dots,y_n) = \sum_i y_i^{(1-\alpha)(1-\rho)} * (1-\alpha)^{(\rho-1)}/(1-\rho) \tag{15}$$

By defining $\sigma = \alpha + \rho - \alpha\rho$ and $C = \frac{(1-\rho)}{(1-\sigma)(1-\alpha)^{(\rho-1)}}$ and multiplying the above expression by C (a constant) we obtain:

$$W(y_1,\dots,y_n) = \sum_i \frac{y_i^{1-\sigma}}{(1-\sigma)} \tag{16}$$

Multiplying the SWF by a constant without changing the relative welfare changes from changes in consumption levels can be done if the SWF is homothetic in its arguments (Johansson-Stenman, 2000). The argument of the SWF is now the income vector $\boldsymbol{y}$. In the Appendix, we prove that the SWF is indeed homothetic in $\boldsymbol{y}$, and by definition of a homothetic function, the constant will pop out.

The changes in income, measured with either CV or EV, should be weighted by the marginal social utility of income α_i:

$$\alpha_i = \frac{\partial W}{\partial y_i} = y_i^{-\sigma}. \tag{17}$$

Note that y_i should be normalized, that is, scaled by the average income so that $y_i = \frac{Y_i}{\overline{Y_i}}$. The parameter σ contains both the relative risk aversion and relative inequality aversion parameters and is thus a mixture of risk aversion and ethical values. However, usually only one parameter is used (e.g. Boadway, 2006; Johansson-Stenman, 2005; Tol, 2005), as it is easier to vary one parameter instead of two and the results are easier to interpret; sometimes, however, both parameters are varied separately (Adler, 2013). Kaplow (2010) suggests that if a simulation uses the SWF in the above form and with σ, it should be interpreted as 1) a utilitarian welfare function with a constant relative risk aversion (CRRA) parameter or 2) an egalitarian (strictly concave) SWF with an inequality aversion parameter and with risk-neutral individuals or 3) any combination in between. It should be noted that as $\frac{\partial\sigma}{\sigma\rho} = 1 - \alpha < 0$, *if* $\alpha > 1$, the inequality aversion parameter actually turns into an equality aversion parameter, as the weight given to lower-income groups decreases for higher values of ρ. Thus, as noted by Azar (1998), the use of two parameters can produce misleading results.

Drawing on empirical evidence on choice under uncertainty (Dasgupta, 1998) and on choice experiment surveys (Johansson-Stenman et al., 2002), Johansson-Stenman (2005) suggests that σ is on average around 2. Kaplow (2010) states that the estimates of most economists fall between 1 and 2 with no clear consensus, but that a range of parameter values should be applied so that results for different parameters can be presented. Anthoff et al. (2009) conclude in their theoretical review that it is almost impossible to determine the appropriate value without ethical judgements, making the case of using multiple values in a sensitivity analysis even stronger. Tol (2005) use weights between 0.5 and 1.2 in their analysis. Hallegatte et al. (2016) state that 1.5 is a standard weight, albeit without much discussion, but at the same time recommend that a sensitivity analysis should be conducted with different weights.

An interesting special case is when $\sigma = 1$, the weight is then $\alpha_i = \frac{\overline{Y}}{Y_i}$ and the weighted change in welfare for individual i is $WTP_i^{weighted} = WTP_i * \left(\frac{\overline{Y}}{Y_i}\right)$. This weighting rule captures the idea that each person's willingness to pay relative to his or her income is given the same weight in order to "equalize the votes" between different individuals (Boardman et al., 2006). We call this weighting rule *Weights based on the income-weighted average benefits of individuals*. This line of thinking can be linked to an earlier discussion of benefit incidence by Ebert (2003). As the average benefit for a person is defined by $b(p,q,y) = B(p,q,y)/y_i$, the $WTP^{weighted}$, or weighted willingness to pay, is defined by $b(p,q,y)*\overline{Y}$ for each person. In this manner, each person's (average) benefit per income unit is scaled by the same average income factor, a procedure that arguably allows equal standing for each person's preferences (e.g. Boardman et al., 2006).

It is also of interest to ask how the aggregated benefits change if this weighting rule is applied. In Section 2.1 it was proven that the average benefits per person are increasing with income if $\eta(WTP,y) > 1$. As wealthier people have a lower weight if this weighting rule is used and proportionally larger values for the benefits in the case of $(WTP,y) > 1$, the weighting rule tends to lower the aggregated benefits. If $\eta(WTP,y) < 1$, the average benefits are higher for lower-income groups, who now receive a higher weight compared to wealthier ones. In this case, the weighting rule tends to make the aggregated benefits higher and the CBA is more likely to yield positive net benefits. As was shown in Section 2.3, this seems to be the case with most environmental goods.

Also with any other (positive) choice of inequality parameter value, weighting increases the aggregate benefits for projects with $\eta(WTP,y) < 1$ compared to projects assessed using unweighted CBAs. If the weighting factor is higher than 1 - for example 2, as proposed by Johansson-Stenman (2005) - a weighted CBA makes projects with $\eta(WTP,y) < 1$ even more attractive and likely to pass the ABC test. However, a caution about the use of very high inequality parameter values is in order here: Very high inequality parameters can make the weight of low-income individuals so high that the weighted WTP rises to the point where the weights increase the aggregate benefits of "luxury" projects with $\eta(WTP,y) > 1$. With an inequality parameter of 1, that is, the average-benefit approach, this problem does not occur. In Section 5, we explore empirically how the results of a CBA change with changes in the weighting parameter.

3.4. Equal Welfare Changes Among Individuals

The practice of *using the same benefit values for similar kinds of losses and gains in different regions and income groups* has gained popularity, mostly in the assessment of climate change impacts. For example, as early as the beginning of the 1990s, global cost estimates were used to interpolate climate damages for the US (Cline, 1992; Nordhaus, 1991, 1994). Typically, uniform values are used, a response to the controversy of having different values for a statistical life (VOSL) in countries which differ in their income level (Johansson-Stenman, 2000). This is also the case in most health related applications, e.g. such as valuing the costs related to air pollution (e.g. Muller and Mendehlsohn, 2009; Heo et al., 2016). According to Johansson-Stenman (2000), using an equal monetary value for life or any other good is theoretically correct under the following condition:

$\frac{\partial w}{\partial u_r}\frac{\partial u_r}{\partial y_r}WTP_r = \frac{\partial w}{\partial u_p}\frac{\partial u_p}{\partial y_p}WTP_p$, in which subscript r stands for high-income people and subscript p for low-income people. If we assume that the weights $\frac{\partial w}{\partial u_r}\frac{\partial u_r}{\partial y_r}$ are the same as those introduced in Section 3.3, the equation simplifies to $y_r^{-\sigma}\alpha_r = y_p^{-\sigma}\alpha_p$. If the weights based on income-weighted average benefits are applied, then $\frac{\overline{Y}}{Y_p} * WTP_p = b_p = \frac{\overline{Y}}{Y_r} * WTP = b_r$, and $\frac{\partial WTP(p,q,y)/y}{\partial y} = 0$ and the requirement is that the benefits are proportionally distributed; that is, the income elasticity of WTP = 1. If the weights are based on the SWF approach and weights higher than $\sigma = 1$ are applied, the benefits need to be progressively distributed (income elasticity of WTP > 1) for the condition $\frac{\partial w}{\partial u_r}\frac{\partial u_r}{\partial y_r} WTP_r = \frac{\partial w}{\partial u_p}\frac{\partial u_p}{\partial y_p} WTP_p$ to hold.

Although often not theoretically correct (Adler, 2013), using the same value for goods such as life, health change or change in the quantity of environmental is morally superior, at least in the absence of any other explicitly defined weights (e.g. Azar, 1998). Moreover, by using the same value estimates for life, health or environmental goods, for example, one avoids the somewhat arbitrary choice of weight factors. The logic can also be defended with reference to the discussion on which numeraire should be used to evaluate welfare changes. As noted by Dreze (1998), if the numeraire were the environmental gain or loss instead of a measure of income, the extent of environmental gain or loss would be measured in equal terms across individuals or regions. However, when monetary estimates are used, the wealthier implicitly have a higher weight for their preferences when converting gains or losses into monetary units. Equal monetary valuation can be seen as an attempt to monetize the environmental losses or gains using either an average WTP across regions or the WTP of a specific individual or region. The difficulty in empirical analysis is to decide whose monetary welfare change is used as the baseline to evaluate the welfare changes of others.

3.5. Region-specific Weights

Yet another approach, one mainly applied in climate change economics, is aggregation over regions using *region-specific or interregional weights* calculated separately for each region using the average income of the region in relation to that of other regions. A region is typically defined as a country, a continent or other unit, such as a NUTS region, a classification used in the EU. Tol (2005) analyzed the effect of weights on global carbon damage estimates using equity weights representing the ratio of the world average per capita income to regional average per capita income raised to the power $-\sigma$, as in Eq. (17). The regional damages were then aggregated by this rule. The sensitivity analysis in Tol (2005) revealed that the global damages were sensitive to the choice of the risk/inequality parameter such that the higher the parameter value was, the higher the aggregated damages were.

The weakness of this approach is that individual damages are not weighted: Intra-regional distributional concerns cannot be corrected by this method. This has been the usual approach used in the integrated assessment models such as FUND (e.g. Anthoff et al., 2009), which gives different equity weights to different regions but considers the change in average consumption over time. However, lately the effects of much finer individual resolution have been estimated: both Dennig et al. (2016) and Anthoff and Emmerling (2016) simulate how the addition of intraregional weighting affect the damage figures, thus applying the weights in their theoretically correct SWF based form.

Despite recent advances, it is likely that the region-specific weights will be used in many applications in the future and figures derived with this weighing approach have political relevancy. It is thus interesting to compare this rule to individual-specific (intra-regional) weighting rules. Take two persons from a specific region, one with an above-average, one with a below-average income. Now consider that the aggregated WTP of that region is weighted based on the region's average per capita income compared to the world average per capita income; the WTP of each individual (a part of the aggregated WTP) is weighted by that same weight. Both a high-income and low-income person living in the same region thus have the same weight, even though a low-income individual should have been given a higher weight based on the social marginal utility of money (Section 3.3) than a high-income individual. At the end of the day, region-specific weighting underestimates the social marginal utilities of lower-income groups and overestimates those of higher-income groups.

4. Empirical Approach

In this section, the distributional weighting schemes derived in Section 3 are applied to data from a state-of-the-art contingent valuation study on the benefits of improved water quality in nine countries around the Baltic Sea in Northern Europe. The data are well-suited for analyzing the effect of weighting on environmental values and the results of a cost-benefit analysis. First, as we have both individual- and country-level data on income and WTP, we can empirically test several weighting approaches and both individual and regional weights. Second, even though the countries studied all lie along the Baltic Sea, they are heterogeneous in income, and thus region-specific weighting (Section 3.5) is likely to have a substantial effect on the estimated values. The income distribution within the countries is more equal than in many other parts of the world. For example, if measured by the Gini coefficient, Russia is the most unequal country in the sample, but still only 62nd in the World Bank Country Ranking (World Bank, 2016). The Nordic countries are among the lowest-ranked countries by the same measure. Individual-specific (Sections 3.3–3.4) weights might have a more dramatic effect in a sample including countries with a more unequal income distribution.

4.1. Description of Data

The data originate from a contingent valuation survey conducted in the nine littoral countries[1] of the Baltic Sea that elicited people's WTP for a change in the marine environment (Ahtiainen et al., 2014). Contingent valuation is an established stated preference valuation method, commonly used to value changes in environmental quality (Mitchell and Carson, 1989; Carson and Hanemann, 2005; Alberini and Kahn, 2006). The survey was designed in a process of international collaboration during the years 2010–2011 and implemented in 2011 using identical questionnaires translated into the relevant national languages. The tailored design method set forth by Dillman et al. (2009) was closely followed in the design and implementation of the survey.

Random samples were drawn from the national population in all the countries except Russia, where two samples were constructed, one from areas on the Baltic Sea coast and the other from the remainder of the country. Data were collected using Internet panels in Denmark, Estonia, Finland, Germany and Sweden, and face-to-face interviews in Latvia, Lithuania and Russia. In Poland, both Internet panels and face-to-face interviews were employed (see Ahtiainen et al., 2014 for details on the implementation).

The survey elicited people's willingness to pay for improved water quality in the entire Baltic Sea in the form of reduced eutrophication. The environmental change was described verbally and visually using a five-step water quality ladder as well as color maps depicting water quality in different parts of the sea before the change and after it (the year 2050). The baseline and policy conditions used for the survey drew on nutrient loading predictions from a marine basin model that were translated into discrete water quality levels and their descriptions (Ahlvik et al., 2014; Kiirikki et al., 2001, 2006; Maar et al., 2011). The survey described the payment vehicle as an annual Baltic Sea environmental tax for each individual and business in the littoral countries. Following a standard practice to avoid anchoring in stated-preference valuation surveys, the questionnaire did not provide any information on the actual costs of the project or their distribution among individuals. Before the valuation question, the survey presented reminders of substitutes and the budget constraint. WTP was elicited with a payment card, which had 18 bids, including 0.

[1] These countries are Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, Sweden and Russia.

Table 1
Country-specific sample size, mean income and mean WTP.

Country	Sample size	Mean monthly net income (in 2011 PPP-adjusted €)[a] (population income in parentheses)	Mean willingness to pay (in 2011 PPP-adjusted €)
Denmark	1061	2275 (2385)	34.7
Estonia	505	583 (542)	27.6
Finland	1645	1890 (2031)	45.3
Germany	1495	1641 (1827)	27.7
Latvia	701	311 (428)	6.1
Lithuania	617	205 (387)	10.5
Poland	2029	495 (492)	14.3
Russia	1508	338 (462)	10.2
Sweden	1003	1858 (2024)	84.2

[a] Source of population income: Eurostat (2013a); for Russia: Rosstat (2010).

Consequentiality (Carson and Groves, 2007) was invoked with respondents motivated by saying that their "answers would help governments around the Baltic Sea to develop appropriate water quality improvement programs". In addition, examination of the survey responses revealed that the majority of respondents cared about water quality in the Baltic Sea. The final data included 10,564 respondents, with a minimum of 500 per country (Table 1).

The WTP and income data used in the empirical analysis come from the contingent valuation data set. For the comparison of costs and benefits, cost estimates of water quality improvement measures are readily available, as the results of the valuation study have already been included in a standard CBA (Hyytiäinen et al., 2015). Thus, in addition to examining the effect of distributional weighting on environmental values, we can study how the results of a CBA change when we apply different weighting methods.

4.2. Weights in the Empirical Analysis

The theoretical determination of different weights was discussed in Section 3. This section covers some practical considerations. In Section 3.3 we defined the normalized income of an individual i as $y_i = \frac{Y_i}{\overline{Y_i}}$. Here we need to define Y_i and $\overline{Y_i}$. As we are interested in the after-tax income distribution, Y_i is the average after-tax monthly income of individual i. We convert the incomes in different currencies to euros using the purchasing power parity (PPP) adjusted exchange rates. These rates reflect the purchasing power of currencies in different countries or regions and are preferred to financial exchange rates because they capture the differences in price levels and thus lead to more meaningful international comparisons (e.g., Ready and Navrud, 2006).

The second component, $\overline{Y}$, is the average income. This is the average after-tax income of the entire population that the project would involve. In our case, it is the average monthly income of the population living in the coastal countries of the Baltic Sea. Accordingly, the normalized income y_i of individual i becomes:

$$y_i = \frac{Monthly\ average\ after - tax\ income\ of\ individual\ i = Y_i}{Monthly\ average\ after - tax\ income\ in\ countries\ around\ the\ Baltic\ Sea = \overline{Y}} \tag{18}$$

As mentioned in Section 3.5, it is common in climate change economics to use region-specific weights that are derived by scaling the monthly average income in a region (in this case country j) to the global (in this case the Baltic Sea region) average income. For this purpose, y_i can be broken down into two components:

$$y_i = \frac{Monthly\ average\ after\ tax\ income\ of\ individual\ i}{Monthly\ average\ after\ tax\ income\ in\ country\ j = \overline{Y_j}} * \frac{Monthly\ average\ after\ tax\ income\ in\ country\ j}{Monthly\ average\ after\ tax\ income\ in\ countries\ around\ the\ Baltic\ Sea = \overline{Y}} \tag{19}$$

The full weight is then given by:

$$a_i = \left(\frac{Y_i}{\overline{Y}}\right)^{-\sigma} = \left(\frac{Y_i}{\overline{Yj}}\right)^{-\sigma}\left(\frac{\overline{Yj}}{\overline{\overline{Y}}}\right)^{-\sigma} \tag{20}$$

As can be seen from Eqs. (19) and (20), the weight for individual i can then also be broken down into two parts: the individual-specific weight $\left(\left(\frac{Y_i}{\overline{Yj}}\right)^{-\sigma}\right)$, which corrects for the distributional impacts within the country or region, and the region-specific weight $\left(\left(\frac{\overline{Yj}}{\overline{Y}}\right)^{-\sigma}\right)$, which corrects for the distributional impacts between different countries or regions. As noted in Section 3.5, the distributional impacts within countries are often neglected in empirical analyses and thus only include the latter multiplicand of the above equations.

Last, the social inequality parameters used in the SWF approach (Section 3.3) need to be specified. A range of parameter values from 0.5 to 2 is applied in the empirical analysis, thus covering the typical range of weights suggested in the literature. The average-benefit approach (Section 3.3) is included as it uses a value of 1 for the inequality parameter σ. We compare the results of using only region-specific weights to the theoretically correct approach of using both region-specific and individual-specific weights (hereinafter "full weights"). We also discuss the implications of choosing some specific WTP as a proxy for all other individuals' welfare change (Section 3.4).

5. Results

5.1. Mean and Aggregate WTP With Intraregional Weights

Table 2 presents the effects of using intraregional (i.e., individual-specific) weights on individuals' WTPs in the countries in the sample. The effect is the outcome of the first factor in Eqs. (19) and (20). These adjusted WTPs would be the appropriate welfare measures for the welfare change if each country studied the benefits and costs in isolation, that is, without regard to the international context. In that case, this analysis would suffice without further weighting the benefits by the region-specific weights. This individual-specific analysis is usually left out of estimates relating to climate change damages.

The first figure in each of the cells in Table 2 corresponds to the mean individual WTP and the second to the aggregated WTP in the country. For comparison purposes, the second column reports the unweighted WTP (as in Table 1). Columns 3, 5 and 6 present the WTPs for SWF-based weights with the inequality parameters 0.5, 1.2 and 2, respectively. Column 4 applies the weight rule of counting average benefits, which is equivalent to applying SWF approach with an inequality parameter of 1. Tables 3 and 4 follow the same logic.

Table 2 also presents two estimates for the average income elasticity of WTP for each country. The first is based on a simple relation between WTP and income in logarithmic form. The second (reported in Ahtiainen et al., 2014) is estimated from a more complex WTP function with additional explanatory variables.[2] For simplicity, the weights and WTPs have been calculated from the income and WTP data alone, and thus the first income elasticity better explains the changes in the WTP due to weighting, while the second is theoretically more correct.

In the countries with the lowest income elasticities of WTP, Estonia and Germany, the mean WTPs react the most to the introduction of the intraregional weights. The introduction of other explanatory variables increases the income elasticity in these countries but only slightly, and the income level seems to have almost no effect on the WTP. As the income elasticity is lower than 1 in all of the other countries for both of the elasticities modelled, the introduction of intraregional weights increases the mean WTP and thus the aggregated total benefits; that is, the low-income groups benefit more from the environmental change

[2] These variables describe income, age, gender, education level, distance to the coast, recreational use of the sea, knowledge on the effects of eutrophication and attitudes.

Table 2
Effect of intraregional weights on the mean and aggregate willingness to pay and income elasticity of WTP. All WTP estimates are in PPP-adjusted 2011 €. In columns 2–6, the first figure corresponds to the mean WTP (€) and the second figure to the aggregated WTP in the country (million €).

Country	Weighting approach					Income elasticity	
	Unweighted	SWF approach, $\sigma = 0.5$	Average benefits (SWF approach, $\sigma = 1$)	SWF approach, $\sigma = 1.2$	SWF approach, $\sigma = 2$	Income elasticity of WTP with income as the only explanatory variable	Income elasticity of WTP with a larger number of explanatory variables
Denmark	34.7/137	36.3/144	41.7/164	45.5/180	75.98/301	0.35	0.41
Estonia	27.6/27	31.8/31	44.4/44	53.44/53	144.97/143	0.02	0.26
Finland	45.3/164	47.4/171	54.3/196	58.3/211	94.2/341	0.50	0.27
Germany	27.7/1892	31.8/2173	42.1/2876	48.8/3334	103.3/7057	0.07	0.12
Latvia	6.1/10	6.7/11	8.8/15	10.3/17	23.5/40	0.52	0.51
Lithuania	10.5/26	12.0/30	16.3/41	19.4/49	28.7/72	0.30	0.35
Poland	14.3/352	14.9/367	16.9/416	18.2/448	24.5/603	0.70	0.21
Russia	10.2/831	10.3/839	11.8/961	12.9/1051	22.8/1857	0.40	0.39
Sweden	84.2/637	86.4/654	95.7/724	102.5/775	162.3/1228	0.53	0.43

than the high-income groups in relative terms (Ebert, 2003).

5.2. Mean and Aggregate WTP With Interregional Weights

The water quality of the Baltic Sea is an international environmental issue which concerns all the countries that lie on the coast. The actions of one country have only a limited effect on the water quality, and cost-effective solutions require international cooperation (Hyytiäinen et al., 2015). In an international context due consideration must be given not only to the individual-specific income distribution within countries but also to the differences in income levels between countries. The region-specific (interregional) weights (the second parts of Eqs. (19) and (20)), that is, the weights defined in Section 3.5, are the tool for this adjustment. In this data set, each country is treated as a region and the region-specific weight is thus calculated for each country in the sample. The effects on the mean WTPs are shown in Table 3. Using the SWF approach with the inequality parameter 0.5 and the average-benefit approach, the total WTP (presented in the last row) is lower than the unweighted total WTP. The reason for this outcome is that the low-income groups in the high-income countries – notably Germany – end up receiving a lower weight than they had in the unweighted CBA. If we increase the inequality parameter σ to between 1.2 and 2, the decrease in the aggregate WTP in the high-income countries is compensated by the simultaneous increase in the total WTP in the low-income countries – most notably Russia – and the aggregate WTP increases compared to the unweighted case. Thus, the effect of weighting switches from negative to positive as we increase the inequality parameter.

Table 3
Effect of interregional (region-specific) weights on the mean and aggregate willingness to pay. All WTP estimates are in PPP-adjusted 2011 €. The first figure corresponds to the mean WTP (€) and the second figure to the aggregated WTP in the country (million €).

Country	Unweighted	SWF approach, $\sigma = 0.5$	Average benefits (SWF approach, $\sigma = 1$)	SWF approach, $\sigma = 1.2$	SWF approach, $\sigma = 2$
Denmark	34.7/137	28.55/103	23.5/85	21.8/78	16.0/58
Estonia	27.6/27	31.7/31	36.3/36	38.3/38	37.7/47
Finland	45.3/164	38.2/138	32.2/116	30.1/109	22.9/83
Germany	27.7/1895	23.6/1612	20.0/1366	18.8/1284	14.5/991
Latvia	6.1/10	9.3/16	14.3/24	16.9/29	33.3/56
Lithuania	10.5/26	19.0/47	34.5/86	43.8/109	113.5/282
Poland	14.3/353	16.6/409	19.2/473	20.3/500	25.7/633
Russia	10.2/831	13.3/1084	17.2/1401	19.1/1556	29.1/2371
Sweden	84.2/637	74.8/566	66.3/501	63.2/478	52.2/395
Total WTP	4070	3978	4037	4116	4918

5.3. Mean and Total WTP With Full Weights

The figures in Table 4 have been calculated by taking into account both the individual- and region-specific weights. This accounts for the full effect in Eqs. (19) and (20).

When the weights are applied in the theoretically correct, full form, the aggregate WTP is higher than the unweighted WTP for all the inequality parameter values. This is expected, as the income elasticity of WTP is lower than 1 in all of the Baltic Sea countries. For a value of 2 for the inequality parameter – considered plausible by many economists (Section 3.3) – the total WTP is over three times higher than in the unweighted case, and the mean WTP is consistently higher in the countries with the lowest mean income. For example, the weighted mean WTP is almost ten times higher in Lithuania than in Denmark. This phenomenon, which results in values that are hard to justify any longer by economic reasoning, Adler (2013) calls “overcompensating”. The least variance in the values between countries is achieved by counting the average benefits such that each individual in each country receives the same weight relative to his or her income. This approach, whose results are presented column 4, yields benefits of 1.2 billion euros, a figure 30% higher than in the unweighted case.

Table 4
Effect of full weights on the mean and aggregate willingness to pay. All WTP estimates are in PPP-adjusted 2011 €. The first figure corresponds to the mean WTP (€) and the second figure to the aggregated WTP in the country (million €).

Country	Unweighted	SWF approach, $\sigma = 0.5$	Average benefits (SWF approach, $\sigma = 1$)	SWF approach, $\sigma = 1.2$	SWF approach, $\sigma = 2$
Denmark	137	28.4/108	29.9/102	28.6/103	35.05/126
Estonia	27	36.5/36	58.32/57	74.2/73	250.6/248
Finland	164	40/140	38.6/145	39.1/142	47.6/172
Germany	1895	27/1848	30.4/2076	33/2258	54.4/3719
Latvia	10	10.3/17	20.4/35	28.4/48	128/217
Lithuania	26	21.8/55	53.7/135	81/204	310.5/780
Poland	353	17.2/425	22.7/559	25.9/638	47.6/1173
Russia	831	13.5/1096	19.9/1623	24.2/1971	65.3/5320
Sweden	637	76.6/580	75.3/570	77.9/582	100.6/761
Total WTP	4070	4404	5272	6019	12,516

A comparison of Tables 3 and 4 prompts several interesting observations. As the income elasticity of WTP (Table 2) is below 1 in all countries, the mean WTPs calculated with only the region-specific weights in Table 3 are lower in all countries than the mean WTPs with the full weights. The greatest difference is in those countries with very low income elasticities of WTP (i.e., Estonia and Germany). This is because the welfare changes of low- and high-income individuals are weighted with the same weight within a given country (see Section 3.5). It can be noted that in this respect region-specific weights discriminate against the low-income population, especially in high-income countries. As we increase the inequality parameter σ, the difference between the full and region-specific weights becomes larger: For example, using $\sigma = 2$ for Estonia the full weight results in a mean WTP that is over five times higher than the mean WTP calculated using only the region-specific weight.

The most striking observation when comparing Tables 3 and 4 is that if only the region-specific weights are used, the total aggregated WTP is lower than in the unweighted case for inequality parameters $\sigma = 0.5 - 1$. As the aggregate WTP increases with the full weights, the inclusion of only the region-specific weights clearly adjusts the WTP in the wrong direction.

5.4. Effects of Weighting on the Results of a Cost-benefit Analysis

The total WTP (benefits) can be compared to the costs of a program to assess the economic efficiency of the water quality improvements envisaged for the Baltic. The cost estimates in Table 5 below originate from Hyytiäinen et al. (2015), who calculated the costs of the nutrient abatement measures required to meet the environmental state that corresponds to the after-policy state presented in the contingent valuation survey and thus to the benefit estimates. The costs are divided among the coastal countries according to the cost-effective solution; that is, measures are implemented in the countries where they are the least costly. However, this solution does not necessarily mean that if the abatement measures are actually undertaken, the costs will be paid by each country in accordance with the solution.

The total costs of the program are estimated to be around 1500 million euros annually (Hyytiäinen et al., 2015). The main result of the CBA does not change: the aggregate benefits exceed the aggregate costs in the unweighted case and when using region-specific and full weights. The benefits based on the full weights are the ones that determine the cost-effectiveness of the project as a whole. In this case, the results of the CBA clearly support implementation of measures to achieve nutrient abatement.

It is important to point out that in general, in such an international context, there is no intergovernmental decision-maker that would use the information to make an optimal decision leading to the common dilemma of the Tragedy of the Commons (Hardin, 1968). However, for many environmental problems, an international governing body exists that hosts the negotiations to form a convention to solve the problem. In this case, the results of the CBA can be seen more as part of the information that international negotiations should be based on, rather than a social choice rule (Nyborg, 2014). In the practical application presented in this paper, the relevant regional body is HELCOM (Baltic Marine Environment Protection Commission), which consists of the nine countries surrounding the sea and the EU. HELCOM governs the Convention on the Protection of the Marine Environment of the Baltic Sea Area, and agrees on nutrient reduction targets for each country (HELCOM 2013). The results of the CBA, including the implications of applying the distributional weights, could be used to inform and justify the allocation of nutrient input reductions in the negotiations carried out by the HELCOM contracting parties.

Table 5
Estimated costs for the desired water quality improvements.
Source: Hyytiäinen et al., 2015, Table 4, Policy Goal III.

Country	Costs M€/year
Denmark	267
Estonia	36
Finland	52
Germany	99
Latvia	55
Lithuania	83
Poland	580
Russia	106
Sweden	211
Total	1489

The results obtained by the use of intraregional weights can be used by the individual governments and are more important purely from the decision-making sense. The countries can use this information in the international negotiations e.g. to decide their level of commitment. It is interesting to note how the introduction of intraregional weights affects the cost-benefit assessment and the net benefits within the focal countries: The estimated costs for each country in Table 5 indicate that in some countries the unweighted aggregate WTP would not exceed the costs, but that the results would change with the introduction of intraregional weights (Table 2). For example, for Estonia, the unweighted total WTP is 26 M€/year and the costs are 36 M€/year. With the inequality parameter $\sigma = 1$, that is, when applying the average-benefit approach, the intraregional weighting would result in an aggregated WTP of 44 M€/year, as seen in Table 2. Thus, if the distributional impacts are taken into account within the country, it would be beneficial for Estonia to participate in the program even if the costs are shared according to Table 5. In Poland as well, the individual-specific weighting results in positive net benefits if the inequality parameter used is 2 or higher.

An additional question is whether the costs as well should be weighted. On the theoretical level, we can consider two options to finance the costs of the project. The first assumes a government budget resulting from a democratically decided tax schedule. The project has no effect on the labor supply schedule and no direct monetary consequences for individuals. In this case, the costs of the project should not be weighted within the country, as proven by Johansson-Stenman (2005) with the main results referred as *modified Samuelsson rule*, in which only the benefits are weighted:

$$\frac{\sum_i^n \alpha_i MRS_{G_1}^i}{p_1} = \frac{\sum_i^n \alpha_i MRS_{G_2}^i}{p_2} \tag{21}$$

The second option, quite the opposite of the first, is to assume that the government includes changes in the tax schedule and thus that the project has direct monetary consequences for individuals. In this case, we need to know how the costs are distributed among the affected population. Blackorby and Donaldson (1990) have shown that Eq. (1) can be manipulated and rewritten in the following form:

$$CV = (y_1 - y_0) + e(q_0, u_0) - e(q_1, u_0) \tag{22}$$

where $u_0 = u(q_0, y_0)$.

Thus, the WTP can be split into two parts: the first is the change is the change in income, which can be readily expressed in monetary units, and the second is willingness to pay for the change in the state of ecosystem service. The changes in income are thus included in the WTP and should be weighted with same weight as the benefit part of the equation. To be able to weight the costs in this case, we would first need to know how the costs are distributed among the individuals within the country, then use the intraregional weights for this distribution and apply the region-specific weights. Such an analysis is beyond the scope of the present article, as the survey did not specify how the costs would be distributed among regions or individuals.

6. Discussion

Thus far, we have demonstrated how income tends to affect the monetary measures of welfare change and how these effects could – and, in the view of many economists, should - be taken into account in environmental valuation and cost-benefit analysis. In a more practical approach, we have shown how the results of an empirical valuation study are affected by the introduction of distributional weights, much as occurs in a sensitivity analysis. The choice of the weighting scheme and, more particularly, the value of the inequality parameter is more of an ethical question. We point out that the choice not to use any of the weighting schemes; that is, setting the inequality parameter to 0, is a choice itself.

As Nyborg (2014) states, the role of the CBA can be to provide information to support decision-making, rather than to present a social choice rule. In this case, it might be argued that the use of distributional weights confuses the recommendation from the CBA to the policy-makers (Nyborg, 2014). However, an opposing argument could be made that including the sensitivity analysis and weighted results of the CBA would actually improve the information base for the decision-making process, rather than limiting their usability. In our view, presenting the weighted results would show information related to the income elasticity, income distribution and distribution of benefits in a more dense and understandable way than other alternatives and serve to showcase how important the distributional concerns are.

In our opinion the decision to use the average-benefit method, that is, setting the inequality parameter to 1, entails some desirable technical and ethical benefits, and should be included in the sensitivity analysis. It is by some logic a democratically sound weighting scheme as it gives the same weight to each individual's WTP normalized by his or her income. Moreover, by the logic explained in Section 3.3, in the case of proportionally distributed benefits the approach keeps the aggregate benefits at the same level and increases/decreases them for regressively/progressively distributed benefits in a given project. The same is not true for the other weighting rules: It is possible that the social welfare function approach, especially with a very high inequality parameter value, will increase the aggregate benefits even if the benefits are progressively distributed. What is more, the variance in the mean WTP between the countries is lowest for the average-benefit rule, at least in our data. Of course, some might point out that this approach is inadequate because the preferences of low-income people should be weighted even more heavily.

Our data are well suited for a distributional analysis: They include the WTP and the income separately for each individual. In a state-of-the-art stated-preference study, this information is always gathered, but frequently only 30 to 40% of respondents reveal their income (Tyllianakis and Skyrus, 2016). In our data, however, > 90% of respondents provided that information. The valuation was also carried out for the same environmental good at the same time for nine different countries, and thus we can compare the effects of region-specific weights to those of full weights, which also take the income distribution within the countries into account. Our analysis indicates that country-specific weights may correct the aggregate WTP in the wrong direction, with low-income groups receiving a lower weight than they would in an unweighted CBA. This is somewhat alarming, as this a common approach when aggregating climate change damages. Recent papers by Dennig et al. (2016) and Anthoff and Emmerling (2016) have already addressed this issue: Derek et al. (2015) note that taking into account intraregional differences in income can be as crucial as the choice of discount rate. Our findings also indicate that inclusion of intraregional individual-specific weights could have a dramatic influence on welfare change estimates. We do not see why these should not be applied in other cases of environmental amenities next to the climate change damages.

It is sometimes argued that the implementation of weights is not plausible for all valuation studies as it requires information about the incidence of costs and benefits across different individuals or at least population subgroups. This should not be a problem today: In a CBA, the analyst should be able to make some predictions on the incidence of the benefits, use these to simulate the effects of weights on a subgroup of individuals and, based on those effects, estimate the impacts on the CBA results (Adler, 2013).

7. Conclusions

In this paper, we have studied the theoretical foundation and empirical application of distributional weights in environmental valuation and cost-benefit analysis, examining the effect of different weighting schemes on welfare estimates and net benefits. The main conclusions can be summarized as follows:

1) The use of distributional weights can, in many cases, be backed up by economic theory. If however, the decision-maker can also adjust taxes and income transfers simultaneously, and is able to find a Pareto-dominant, politically feasible alternative compared to that suggested by a weighted CBA, the Pareto-dominant option should be chosen. This does not eliminate the need for distributional weights.
2) The income elasticity of welfare measures is the factor that determines the benefit incidence. If it is lower/higher than 1, the benefits are regressively/progressively distributed. The inclusion of distributional weights that are calculated separately for each individual increases the benefits if the benefits are regressively distributed.
3) If the average-benefit approach or logarithmic specification of the SWF approach is used and weights are calculated separately for each individual, the benefits increase/decrease if the benefits are regressively/progressively distributed
4) The choice of weighting rule matters. Region-specific weights – commonly used in climate change economics – do not take intraregional income distribution into account and can correct the results in an unwanted direction.

For a long time, the practice of weighting was abandoned in practical valuation studies and cost-benefit analyses, but the trend now seems to be changing; for example, the World Bank (Hallegatte et al., 2016) has brought distributional weights back into its toolbox. In this paper, we have shown how distributional weights can be formulated and applied in an empirical setting. The weights can be seen as either a straightforward correction for the different income levels of individuals (counting average benefits) or as the use of CBA as a proxy for the social welfare function approach (Adler, 2013), the latter being the most common practice in the rare cases of applied research. It is also possible to use the same monetary value to measure the welfare changes of different income groups, but this is probably not theoretically justified (Section 3.4).

If the standard approach - using CBA as a proxy for the social welfare function - is applied, one still needs to choose the value of the inequality parameter or to perform a sensitivity analysis to show the effects of different parameter values on the welfare measures. The latter is the approach we have applied in our empirical analysis in Section 5. Last, one can (and should) also choose to use the weights in their theoretically appropriate form and thereby correct for both individual-specific (intraregional) and country-specific (interregional) income differences. Considering only interregional issues discriminates in some sense against the low-income people within each region or country, as both the high- and low-income groups within the region end up with the same weights in the intraregional aggregation. We advise against using region-specific weights exclusively.

Our results show that the inclusion of weights can in some cases result in a mean WTP that is almost 30 times higher than the unweighted mean WTP. These extremely high multiples occur when the SWF approach is chosen with high inequality parameter values, 2 in the present example. More conservative results are achieved by choosing to count the average benefits, that is, setting the inequality parameter value to 1. In that case, the aggregate benefit in the region is increased by over 30%, and there is the least variance in the mean WTP between the countries. The total benefits of the program analyzed exceed the costs with all weighting schemes, but the net benefits within the countries change with the inclusion of weights, if game-theoretic concerns are disregarded.

We must point out that this article is not intended as a comprehensive theoretical survey of CBA or even of the topic of how to take distributional concerns into account. We have not applied certain crucial elements from welfare economics, optimal taxes, mechanism design and intergenerational issues. Indeed, an adequate treatment of these would have required an entire book rather than an article. What we have accomplished is to gather economic evidence on how income affects the monetarized welfare changes of individuals and presented options regarding how this effect should be considered.

Future research should encompass more extensive implementation of distributional weights in the sensitivity analysis of environmental CBAs and include individual-specific weights in the climate change economics. There are also approaches that take the heterogeneity of preferences into account, such as the approach of Fleurbaey et al. (2013), which uses equivalent income for interpersonal utility comparisons. These approaches are interesting but not yet widely adopted in economic theory. We have used income and wealth quite freely as synonyms here, as is common in one-period models in economics. Net wealth would be an appropriate measure of the available budget and thus, in addition to income, future environmental valuation surveys should incorporate questions on wealth to improve the construction of distributional weights. Last, we have used observed WTP-income pairs. However, average and total WTP are usually estimated from an estimated WTP function. It is a question for future research to determine whether the weights should also be derived from modelled WTP-income pairs.

Acknowledgements

This article is based on the dissertation research of the first author and funded by the Nessling Foundation (201600396). The second author gratefully acknowledges funding from the Finnish Meteorological Institute. The data collection was supported by the following projects and organizations: the research project PROBAPS; the research project *Managing Baltic nutrients in relation to cyanobacterial blooms*: *what should we aim for*?; the research alliance IMAGE; the BalticSTERN Secretariat at the Stockholm Resilience Centre, Stockholm University; the German Federal Environment Agency; and the Swedish Environmental Protection Agency (EPA).

We would also like to thank the BalticSTERN team, consisting of researchers from all the nine Baltic Sea states, for their collaboration in data collection and their willingness to share the data. Special thanks are due to Janne Artell from the Natural Resources Institute (Luke) for support in the data collection stage. For valuable comments and sparring, we thank Adriaan Perrels from the Finnish Meteorological Institute, and Pauli Lappi from the University of Helsinki.

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II

Economics of Disasters and Climate Change
https://doi.org/10.1007/s41885-018-0038-1

ORIGINAL PAPER

Overadaptation to Climate Change? The Case of the 2013 Finnish Electricity Market Act

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Received: 12 June 2018 / Accepted: 27 December 2018/Published online: 20 February 2019

Abstract

In this paper, we put forward a definition of over-adaptation in disaster risk reduction (DRR) and climate change adaptation (CCA) projects. We detail an illustrative case in which the response to extreme weather risk while aligned with the goals of CCA, is implemented beyond the economically efficient scale. We undertake a cost-benefit analysis of the 2013 Finnish Electricity Market Act, enacted partially as a reaction to long, storm-induced electricity blackouts experienced after 2000. The Act imposes strict requirements on electricity distribution companies as regards the duration of blackouts. Meeting these requirements entails investments amounting to billions of euros. As a benefit, we quantify the avoided cost from the blackouts for households and producers. Our results, derived from Monte-Carlo simulations, show that for urban areas, the net expected value is positive. However, in rural areas less strict requirements could have been economically more efficient. Our results indicate that distributional impacts and correspondence between those who benefit and those who pay the costs should be taken into account in DRR and CCA policies that require large-scale investments. We also note that the population affected by a disaster may not accept DRR and CCA that are successful in terms of regulation and implementation. This applies when societal and individual preferences do not coincide.

Keywords Economic analysis · Electricity grid · Energy policy · Policy assessment · Public good provision · Climate change adaptation

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Introduction

Economic Analysis of Disaster Risk Reduction and Climate Change Adaptation Measures

Various measures have been implemented or proposed to reduce the impacts of extreme weather events on, and the increasing threat of climate change to, communities, the economy and societies, (e.g. Hallegatte 2009; Konrad and Thum 2014). The goal of such measures is to reduce the exposure and vulnerability of people and assets to natural hazards and climate change and thereby to mitigate their impacts (IPCC 2012). Both climate change adaptation (CCA) and disaster risk reduction (DRR) are cross-cutting policy fields, implying that the respective goals are seldom the only goals of a given sectorial policy or measure. For example, in the public sector, DRR and CCA goals are pursued by first integrating relevant DRR and CCA policy instruments into sectorial policies and then ensuring that the sectorial policy goals are harmonised with the goals of DRR and CCA. (COM 2013; Rivera et al. 2015; Pilli-Sihvola and Väätäinen-Chimpuku 2016).

From an economic perspective, there are several criteria for assessing DRR and CCA policy instruments. The Potential Pareto Improvement (PPI) criterion states that the aggregate level of benefits should exceed the costs (e.g. Freeman et al. 2014). A stricter criterion of Pareto optimality requires optimality in the sense that the aggregate benefits of the policy instrument are maximised by equating the marginal benefits to the marginal costs (e.g. Mendelsohn 2012). Whether these criteria are met can be determined by using cost-benefit analysis (CBA). CBA and cost-effectiveness analysis are traditional tools for determining the economic efficiency of public sector policies and projects (Boardman et al. 2006; Smith et al. 2017) and they have also been used extensively for analysing DRR and CCA measures (Shreve and Kelman 2014).

The aim of this paper is to analyse whether over-investment in DRR and CCA occurs, and how the public reacts to major infrastructure investments whose costs they must eventually bear. In the process, we clarify issues related to applying CBA in CCA- and DRR-related investments. We undertake an in medias res social CBA on the amended Finnish Electricity Market Act, passed in 2013 (588/2013). Among its other goals, the Act seeks to decrease the susceptibility of the electricity network to extreme weather and to make distribution companies adapt to changing weather patterns. This has required major investments in resilient electricity distribution networks. The measures required by the Act sparked an intense public debate, as they were followed by substantial increases in the distribution rates (in Finland, production and distribution are separated), and raised the question of whether the policy was an overreaction from an economic point of view. As a sizable investment in DRR and CCA with quantifiable benefits, costs and uncertainty, the project serves as a good case for using a CBA to evaluate DRR and CCA measures from an economic perspective.

Based on the analysis in Shreve and Kelman (2014), a considerable majority of the cost-benefit analyses in the literature have concluded that investing in DRR and CCA measures is beneficial; that is, benefits exceed costs. However, this evidence alone does not warrant the conclusion that DRR and CCA investments are economically efficient and advisable. Indeed, the analysis in Shreve and Kelman (2014) indicates that ex-ante CBAs showing that benefits do not exceed costs are not reported in the literature: no investment was made and no study published. In other words, the CBAs reported suffer from publication bias in that only highly positive or highly negative results have been published (on publication bias, see Easterbrook et al. 1991; Møller and Jennions 2001; in the CBA literature, see Bell et al. 2006) and the hazards studied have been based on the ease of calculating the benefits (Shreve and Kelman 2014). The CCA options reported have been almost exclusively favourable ones, although occasional reports of maladaptation have appeared (Noble et al. 2014).

In section "Background to the Case Study", we present the political background of the case study. Second section goes on to provide an economic definition of the case where marginal costs exceed marginal benefits and defines this as over-adaptation. In third section we discuss cost-benefit analysis (CBA) as a method and the data for our case study. Fourth section describes the results and gives a short account of the public reaction to the Act and the public sector's response to this. In fifth section, we consider the limitations of the analysis and prospects for future research. Sixth section concludes with a discussion of the policy implications of the study.

Background to the Case Study

Finland is a highly developed northern European country where long-term policy and cultural development have averted disasters triggered by natural hazards, (see e.g. Pilli-Sihvola et al. 2017). The Finnish approach to security could be said to exhibit highly risk-aversive preferences (Saastamoinen and Kuosmanen 2016); indeed, they approach lexicographic preferences, with the security of the country and its citizens being the most preferred asset regardless of economic considerations. The major risks are extra-tropical cyclones, winter storms and major snow loads, which cause trees to fall on power lines, resulting in long blackouts. Accordingly, one of the goals of the revised 2013 Electricity Market Act was to reduce the impacts of extreme weather on Finnish electricity consumers with due consideration of the altered weather patterns that climate change will bring. Long blackouts such as those experienced in summer 2010 prompted a need to boost investments in the electricity distribution network, and imposing strict requirements on the permissible duration of the blackouts was considered an effective way to do so (Government Proposal HE 20/2013). The policy process to revise the legislation started quite a bit earlier, in 2001.

The first analyses on the need to reform the legislation were undertaken in 2001. These studies (see Appendix for the list of background studies done prior to the 2013 Act) concluded that the law had to be updated to meet the changing environmental and societal conditions and that it had to include measurable targets. As drafting began, various limits on the length of power outages were assessed. The technology was outdated, and major investments were needed to upgrade it to meet the standards for modern electricity and telecommunication infrastructure and societal structures. Moreover, changes in forest management had increased the exposure of the distribution network to storm and snow damage, and this vulnerability had to be reduced. Two storms in 2001, major thunderstorms in 2010 and heavy snow loads in 2011 (see Fig. 4) highlighted the need to overhaul the distribution network.

The requirements of the 2013 Electricity Market Act are an example of a policy instrument that could substantially reduce the impacts of weather extremes and climate change, for the investments it necessitates would eliminate most of the threat of trees damaging power lines. The Act imposes strict requirements on the duration of blackouts: in rural areas (excluding premises without permanent residents) they should not last no longer than 36 h, and in urban areas no longer than 6 h. The transition period for meeting the requirements extends until 2029, with mid-term goals to be reached by 2019 and 2023 (Electricity Market Act 2013). The upshot of these requirements is that electricity distribution companies have to improve the reliability of their networks, mainly by replacing traditional overhead lines with underground ones (Partanen et al. 2012; Saastamoinen and Kuosmanen 2016). The preliminary assessments undertaken prior to the Act indicate that underground cabling is the only way to ensure compliance with the requirements of the Act where the low- and medium-voltage networks are concerned (Partanen et al. 2012). High-voltage power lines in Finland are already weather resilient, as buffer zones are cleared around them.

The three main goals of the 2013 Act (588/2013) are reliability of electricity supply, affordable rates and reasonable service principles (s. 1). The Act contains explicit references to the capability required of the electricity transmission and distribution systems if they are to withstand normal, expected Finnish climate conditions. In this respect, the Act has integrated DRR and CCA needs quite well, and research findings (Gregow et al. 2011) on the changing risk to forests due to climate change were used when the Act was being drafted. The Act (s. 24) also states that transmission rates and conditions need to be equal and non-discriminatory for all consumers. However, the goal of affordable rates for commercial and residential users, justified in terms of strategic goals for economic and social development, partly conflicts with the aims of reliability and reasonable service principles. Compliance with the 2013 Act has required considerable investment on the part of the network companies. The sharp increase in the price of electricity distribution for consumers that followed its enactment led to a major public debate. This and ensuing parliamentary debates, in turn, resulted in the revision of the Act in 2017. The revised Act states that, in principle, price rises should be moderate but that extraordinary costs can justify stronger price increases. The permissible durations for blackouts were not altered. Despite the revision of the Act on 2017, on 28 May 2018, the Ministry of Economic Affairs and Employment, which drafted the Act, ordered an investigation into the price rises and their spatial distribution due to sharp price increases witnessed after the coming into force of the Act.

The ministry commissioned several assessments of the Act during the period 2001–2013. Some of these included economic analyses; for example, Partanen et al. (2006) concluded that a fully underground cable network would be economically feasible only if the avoided cost were 2.5 times higher than the amount estimated at the time of the analysis for a 40-year investment schedule. If the investment had to be made in a shorter time period (for example, prior to 2030, the end of the transition period allowed by the Act), the avoided cost would have to be 5.5 times higher than the estimates at the time. Later, Partanen et al. (2012) concluded that a time limit of 24 h for blackouts in rural areas, the limit considered initially, would not be economically efficient, and that a 36-h time limit would be preferable. However, the report only compared these two options and their economic feasibility. The legislative proposal (Government Proposal HE 20/2013) included an analysis of the avoided-cost based disutility for the consumers, but did not reach the level of detail of a thorough CBA.

Economic Definition of over-Adaptation to Climate Change

Climate change adaptation is the process of adjustment to actual or expected climate and its effects. The IPCC defines adaptation as follows: “In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects”. (IPCC 2014). In economic terms, adaptation seeks to reduce the costs related to climate change and, if possible, to turn the negative impacts into positive ones (Tol 2005). CCA can take place at different scales in economics: the economic agents are households, firms and the public sector. This paper focuses on public CCA. Adaptation can also be further broken down into two types, anticipatory (planned) and reactive (IPCC 2012; Perrels et al. 2013). In the present case adaptation is cast as anticipatory action resulting in protective investments. However, as discussed in section 1.2, the 2013 Electricity Act (and its induced investments) and revision in 2017 are steps in a learning process, one involving anticipation as well as reaction.

Investments and implementation of CCA measures can lead to three types of sub-optimality: 1) *under-adaptation*, which implies a lack of adequate CCA in the face of changing climate (Hanemann 2000; Quentin Grafton 2010); 2) *over-adaptation*, which implies an over-reaction to the problem (Hanemann 2000); and 3) *maladaptation,* which is any action that increases vulnerability to climate change, increases the risk of negative outcomes or diminishes welfare (Barnett and O'Neill 2010; IPCC 2014). Maladaptation has been widely discussed in the literature, and some real-world examples have been presented (Noble et al. 2014). Under-adaptation, or inadequate adaptation, has been identified as a potential threat: the actions taken may not be enough to adapt (Quentin Grafton 2010) or, for instance, the private sector may not have adequate incentives to implement CCA measures (Eisenack 2014). However, the literature on over-adaptation is virtually lacking: the only examples of over-adaptation that we were able to find in the literature were the few in Shreve and Kelman (2014), where the benefit-cost ratio of CCA investments was below 1. Despite the clear economic implications of over-adaptation, no exact definition of it has been provided to date.

Many CCA decisions concern public policies, public goods or goods with characteristics of such goods (non-rivalry and non-excludability); examples include early warning systems or flood control systems. Optimal CCA for a public good, in terms of partial equilibrium, (e.g. Mendelsohn 2012; OCED, 2018) is to maximise the social net benefits from the provision of the (CCA) good:

$$max \sum B_i(Q) - C(Q), \tag{1}$$

where B_i is the net present value of the stream of expected value from the public CCA effort such that $B_i = \int EV(b_{i,\,t})e^{-rt}$, $b_{i,\,t}$ the benefit for individual i at time t, and Q the quantity of the public good. By differentiating with respect to Q, we get the first order condition for the optimal CCA decision, where M refers to marginal changes:

$$\sum MB_i(Q) = MC(Q) \tag{2}$$

Thus, at the optimum, the aggregated marginal benefits should match the marginal cost of provision of the public good. Several remarks are in order regarding the optimality conditions. First, in theory, the differences in the social marginal utility of money should be accounted in the aggregation process, a procedure known as distributional weighting. (e.g. Boadway 2006; Johansson-Stenman 2005; Adler 2016; Nurmi and Ahtiainen 2018). Secondly, the quantity of public CCA policy, or Q, is an abstract measure reflecting the scale of the proposed action. In our case study, for example, the quantity of public policy refers to the extent to which the electric grid needs to be renewed in response to the requirements of the Act. A less strict Act would require a lower renewal rate, which could be interpreted as a lower quantity of CCA in this example. In this sense, the quantity itself can be seen as a function of the requirements of the regulation, such that $Q = Q(\boldsymbol{L})$, in which the vector **L** represents different characteristics of the regulation. In the present case, these characteristics refer to requirements stipulating the allowable length of power outages in urban and rural areas, as well as to the required uptake schedule. Each of these characteristics can be seen as one dimension of the vector **L,** which determines the quantity of the public policy.

The situation we have chosen to analyse is thus far from being a discrete-choice case, in which the only decision would be whether to implement the Act or not. This is true of nearly all public good decisions, such as deciding on the size of a dam (Hallegatte et al. 2012), the scale of proposed green infrastructure to prevent urban storm-water issues (Nurmi et al. 2016; Nordman et al. 2018) or the extent of early warning systems (Holland 2008).

We define over-adaptation as a situation in which a CCA policy instrument and its implementation increase the resilience of individuals and society but lead to a level of adaptation that is not economically efficient. This problem can be defined using a simple formula. Assuming diminishing marginal utility of benefits such that an increase in the quantity of the public good increases the benefits but at a diminishing rate, the formula can be written as follows:

$$\textstyle\sum_i MB_i(Q(\boldsymbol{L})) < MC. \tag{3}$$

If the marginal costs exceed the marginal benefits at some point of provision, less of the public good should be provided; that is, its quantity should be reduced to a level where the marginal benefit equals the marginal costs. However, even at this level of provision, the total benefit of the project can surpass the costs, resulting in a positive benefit-cost ratio or a positive net present value (NPV). This happens if the marginal benefits at lower levels of provision are high enough to compensate for the negative net benefits at higher levels. This situation is depicted in Fig. 1. By contrast, under-adaptation refers to a situation in which the adaptation policy or measure is implemented at a lower-than-optimal level. This is also depicted in Fig. 1.

$$Q^1 : Max\ BCR\left(Q^1\right) = \frac{B^1}{C^1} > 0; NPV\left(Q^1\right) = B^1 - C^1 > 0; MB > MC \rightarrow underadaptation \tag{4}$$

$$Q^* : BCR\left(Q^*\right) = \frac{B^*}{C^*} > 0; Max\ NPV\left(Q^*\right) = B^* - C^* > 0; MB = MC \rightarrow optimal\ adaptation \tag{5}$$

$$Q^2 : BCR\left(Q^2\right) = \frac{B^2}{C^2} > 0; NPV\left(Q^2\right) = B^2 - C^2 > 0; MB < MC \rightarrow overadaptation \tag{6}$$

The optimal level of adaptation was derived from equation (2), which states that at the optimum the expected net present value (NPV) is maximised when marginal benefits and costs are at equal level, as in Figure 1 at level Q^* and in equation (5).

Another commonly used indicator of the efficiency of a policy or measure is the benefit-cost ratio (BCR). For example, Kelman and Shreve (2014) only report the BCRs of DRR and CCA measures, omitting studies that do not report the value. The BCR is a ratio of the net present value of benefits to costs, as shown in equations (4)–(6). As Figure 1 and equation (4) indicate, the ratio is typically highest at a low level of provision (e.g. at $Q < Q^*$). A low level of provision could correspond to the first systematic efforts to cope with climate change and to elementary disaster risk reduction programmes in developing countries. In Shreve and Kelman (2014), extremely high BCRs are reported for drought reduction measures in the Sudan and flood protection measures in India and the Philippines. Similar results are presented in Onuma et al. (2017a, 2017b), a study showing that experience of a disaster reduces the impact of future

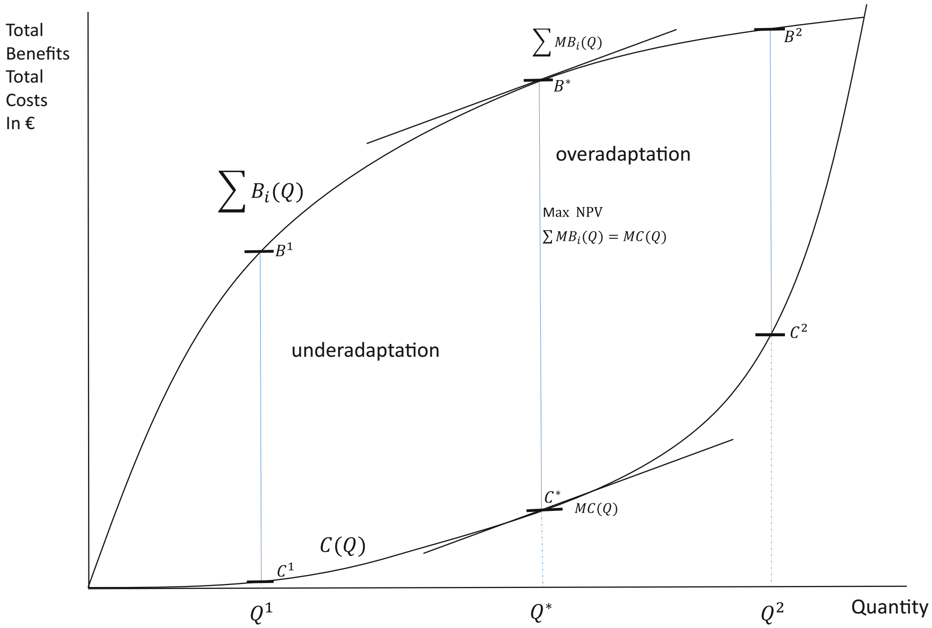

Fig. 1 Optimal adaptation, underadaptation and overadaptation

disasters more in in lower-income than in higher-income countries. However, the optimality of an adaptation policy or measure cannot be evaluated based on the BCR: in Figure 1 the BCR is maximised at Q^1,which corresponds to underadaptation.

We claim that the lack of evidence of overadaptation in the literature is partly due to the misuse of the BCR as a measure of the efficiency of adaptation instead of the NPV, a more appropriate indicator. The latter should be used where a sufficient number of different provision levels of Q are compared with each other.

CBA practitioners are well aware that NPV is the correct measure when ranking different policy options (e.g. Schwab and Lusztig 1969; Boardman et al. 2006; OECD 2018). If all different provision levels could be evaluated, the option with the highest NPV would represent with the optimal level of provision. In Figure 1 this corresponds to Q^*. By contrast, the highest BCR would be found at low provision levels and if used as a decision guideline would result in underprovision of the public good. Some caution should also be exercised when interpreting NPVs: if only one or several provision levels are evaluated, a positive NPV in itself only indicates a scale at which total benefits exceed costs. This can occur at levels of the public adaptation good, reflecting either underadaptation or overadaptation, as seen in Figure 1 and in equations (4)–(6). In such a, case, the interpretation of the NPV and BCR coincide, as pointed out by Shreve and Kelman (2014). Sometimes, even in the economics literature, a positive NPV is interpreted as indicating an efficient adaptation effort. (e.g. Mendelsohn 2012), but as explained above, this is not entirely correct. A thorough analysis should include several different provision levels, preferably spanning a wide range of provision. For example, Hallegatte et al. (2012) include three different levels of flood protection in their analysis: i) one medium-sized dam, ii) two smaller dams and iii) one small dam. Provided that the uncertainty in the analysis can be quantified, the option with the highest NPV should be chosen. In addition, when analysing different provision levels, a marginal analysis should be conducted at the recommended level of provision to determine whether the net benefits could be further increased by either reducing or increasing the provision level of the focal CCA policy or measure.

Finally, uncertainty is an inherent feature of CCA, so much so that the uncertainty related to climate change adaptation decisions has been termed "deep uncertainty". This can refer to any of three factors: 1) no clear consensus on which models should be used to assess the future, 2) an unknown probability distribution of key parameters and 3) an uncertain value of outcomes (Hallegatte et al. 2012). In such cases, it has been suggested that instead of calculating the expected NPV of investment decisions as a basis for decision-making, robust adaptation strategies should be adopted (Dessai and Hulme 2007; Hallegatte 2009; Hallegatte et al. 2012). These include (Hallegatte 2009) no-regret measures, which create benefits even in the absence of climate change; reversible measures, which are easily retrofitted if climate projections prove incorrect; safety margin measures, which reduce the vulnerability of a system at low or no cost; soft measures, which entail institutional or financial changes; reduced time horizon measures, which involve reducing the lifetime of an investment; and strategies that have synergies with mitigation. Based on the robust adaptation theory, a CBA analysing a CCA policy or measure should include at least a qualitative discussion of the robustness of the proposed actions.

Cost Benefit Analysis for the 2013 Electricity Market Act

Methodological Issues

We apply CBA to the reliability requirements of the 2013 Electricity Market Act. We assume cost minimisation for the maximum allowable blackout calculated for a given number of distribution companies in their market areas. As a cost, we include the infrastructure investment in underground cabling required to comply with the Act, calculated based on previous assessments (most notably Partanen et al. 2012). As a benefit, we include the avoided costs of blackouts estimated from blackout data and Willingness-to-Pay surveys and Value-of-Lost-Load (VoLL) calculations for industrial users. The Finnish electricity network for low- and medium-voltage lines has been divided into regional monopolies. This being the case, all the costs will eventually be transferred to the customers as an increased rate for electricity distribution, and they will receive the benefits of the Act. The Act will benefit electricity market companies by decreasing their uncertainty relating to compensation costs from blackouts, costs that in the worst case might amount to 30% of their turnover. (Partanen et al. 2012; Saastamoinen and Kuosmanen 2016). To avoid double counting, we will not consider the decrease in compensation costs as a benefit.

We compare two different levels of provision, urban and rural, as differentiated in the law, and discuss the benefits and costs at the margin. Our results indicate that the Act results in a non-optimal level of provision of public adaptation, a case as yet unreported in the literature.

Smith et al. (2017) point to various factors hindering the use of CBA in many DRR- and CCA-related investments: imperfect valuation methods, sensitivity to assumptions regarding intergenerational preferences (e.g. discount rate), tendency to favour monetised (often tangible market) costs and benefits and inconsistent and often inadequate treatment of non-quantifiable (often intangible non-market) costs and benefits (Atkinson et al. 2008; Boardman et al. 2006; Bonzanigo and Kalra 2014; Florio 2014). In addition, CBA is distributionally insensitive

(Adler 2013, in DRR CBA see Hallegatte et al. 2016) and often fails to analyse the distortionary effects of raising public funds, reflected primarily as impacts on the labour supply. (Boadway 2006; Bos et al. 2018).

Other methods, partly to overcome the obstacles related to the use of CBA, have been used and developed for assessing optimal investment levels of DRR and CCA measures (Smith et al. 2017; Watkiss et al. 2014). Real-option analysis is used in situations where it may be beneficial to wait before the cost-efficient investments are made, one instance being if the investment would benefit from more accurate information. Portfolio analysis is a tool to determine the efficient frontier of investment options, a point where the NPV of the combination of different options cannot be increased without increasing uncertainty at the same time. Portfolio analysis draws on modern portfolio theory, which is based on the idea of maximising profit and hedging risk by spreading the investment optimally over various assets. Portfolio theory can be used for CCA when a number of measures exist to reduce the risk of climate change and there is uncertainty about the benefits of individual measures. Robust decision making is a decision support method used under deep uncertainty, the purpose being to find CCA measures which will function well under various future scenarios (Lempert and Groves 2010; Lempert et al. 2013; Lempert 2014; Watkiss et al. 2014).

In our case, the reported limitations of CBA are not a major concern. First, the investment period of the infrastructure resulting from the renewed policy is estimated at between 50 and 70 years (Partanen 2015). This timeframe involves intergenerational issues over two or three generations; however, the cost of the capital investment will be paid by the customers and, contrary to what Weitzman (2001) suggests, time-declining interest rates should not be applied. Secondly, our case does not involve any major intangible ecosystem or health costs or benefits, but we have taken into account the value of bare forest land that is freed up as the electricity grid is moved from forest to roadsides. All in all, costs and benefits are relatively easy to estimate, as will be shown in the analysis in a later section.

Thirdly, distributional effects are taken into account in our CBA in two ways. In the first, the average willingness to pay (WTP) is applied for all individuals in the affected population rather than using a higher value for wealthier persons. This is the approach recommended by the European Environmental Agency in health economic studies (EEA 2009) and its theoretical aspects are discussed in Adler (2013). However, in our discussion, we take into account what this implies for the results between different regions. In the second, the spatial distribution of benefits and costs has been taken into account in the policy implications, discussed in section 5.

Fourthly, distortionary effects have been left out of the analysis, as there is no adequate research regarding the labour supply effects of changing electricity prices. Most importantly, no alternative methods to CBA, suggested in Watkiss et al. (2014) and Smith et al. (2017), are needed in our analysis, as the Act is already in force and its implementation is under way. There is no opportunity to wait (a requirement for real-option analysis) and no alternative CCA measures can be used by the companies to meet the requirements of the Act (a requirement of portfolio analysis).

Fifthly, uncertainty related to parameter values is quantifiable and the resulting distribution of net benefits can be simulated with the Monte Carlo method. Monte Carlo simulation is a widely used method for analysing the impacts of uncertainty in the parameter values on the results of a CBA. If this uncertainty could be represented with contingent outcomes, one could simply illustrate the results of CBA using different scenarios. However, in the present case we have many uncertain parameter values, which precludes examining all the combinations of values. Our approach is to specify a distribution for each parameter value, take a set of random draws from each distribution, and repeat the trial a number of times. We follow suggestions of Boardman et al. (2006) when specifying the distributions. The resulting histogram can then be used to arrive at statistics about the outcome, such as the expected values and range of NPV and the significance of the results. (Boardman et al. 2006).

Finally, we should point out that our CBA considers *implementation costs and directly related avoided costs* only. A structural and substantial improvement of the electricity distribution network also has induced economic effects. For example, it may help to keep some residents and economic activity in the service area. Furthermore, some of the avoided costs represent actual expenditures rather than inconvenience costs, and these funds can be reallocated for consumption, creating more welfare. Then again, if prices rise more than consumers are willing to pay in a given area, this will create negative effects in the form of reduced purchasing power and areas becoming less attractive places to live. We disregard these spillover effects in the secondary markets in our CBA (Boardman et al. 2006) but discuss them in section 5, as they may be relevant information for cross-cutting policy goals.

Analysis

Estimation of Benefits for Household Consumers

Various methods are used to monetise the increase in the utility from an improvement in the quality or quantity of a good for individuals in society. Direct methods include contingent valuation, indirect ones travel cost or hedonic pricing. The disutility of a blackout for consumers is usually valuated using contingent valuation surveys, which elicit the willingness-to-pay (WTP) to avoid a blackout or willingness-to-accept (WTA) compensation for one.

The most recent such survey in Finland was carried out in 2014 (Matschoss 2014). Rather than the cost per unit of time, the survey asked respondents about their cost per value of lost load (VoLL). In our view, lost load is a harder concept for household consumers to understand than hours without electricity, but in the international literature VoLL is the standard method for reporting the cost of blackouts. However, surveys designed around VoLL often use questions related to inconvenience per time unit (London Economics 2013) and this can be directly converted to cost per time unit. As the average consumer in Finland uses approximately one kilowatt hour of electricity per hour, the VoLL per kilowatt hour is essentially the same as the cost of one hour without electricity.

Converted into hours of blackout, the average VoLL figures in Matschoss (2014) were WTP 1.5€/h and WTA 15€/h. These were assumed to be linear over the duration of the blackout. The high disparity between WTP and WTA suggests behavioural anomalies; the income elasticity of WTP in the study was unrealistically high at 18. The tenfold difference between the WTP and WTA implies that a consumer would not accept 14 euros in compensation for a one-hour blackout that he or she *experienced*, yet would not be willing to pay two euros to *avoid* the same blackout. Given such behavioural anomalies (e.g. Kahneman et al. 1991), these values are not directly applicable in a CBA. The responses to the WTP surveys also suggest that consumers do not necessarily support the lexicographic preferences adopted in national-level decision making (see section 4.4). Interestingly, the high divergence between WTP and WTA in the surveys suggests that an ownership effect obtains among consumers with regard to their right to undisrupted electricity consumption. (London Economics 2013).

London Economics (2013) gathered international estimates for the costs of blackouts to households, and estimated VoLL figures in the UK. The range of WTP estimates in the literature is very wide. The smallest WTP for a one-hour blackout was 0.4€/h (Carlsson and Martinsson 2008). Accent et al. (2008) obtained a value close to 30€/h. The WTP values in London Economics (2013), only about 1€/h. are significantly lower than those in Finland. The WTA values reported, which ranged from 4 to 8€/h under different conditions, are closer to the Finnish estimates.

We apply two different methods to estimate the level of benefits that domestic consumers and industry obtain from the Act. For domestic users, the benefits are evaluated based on the duration of the avoided blackouts. The monetary benefits are estimated by combining the two Finnish contingent valuation surveys (Silvast 2005; Matschoss 2014) and values reported in the international literature (London Economics 2013). We drop the two lowest and two highest outliers in determining the range of WTP values; this yields a lower bound of 1.5€/h (Matschoss 2014) and an upper bound of 15€/h (Accent 2004), all converted into €2015.

The discrete time periods and amounts of lost energy consumption used in the literature have been scaled into a continuous model using the results of Silvast et al. (2005), who drew on a range of blackout durations to create a model very close to a continuous model. The study also provides a detailed description of the Finnish context. According to Silvast et al. (2005), the cost of the first second of a blackout for a household consumer is, on average, 1.7 euros in winter and 1.8 in summer; for a 36-h blackout the values are 368.7 euros and 366.5 euros, respectively. As the costs of blackouts between these two extremes were almost linearly distributed, we fitted a simple linear model (Table 1):

Estimation of Benefits for Industrial Users

We estimate the benefits for industrial users using the production function approach. VoLL is the appropriate measure as it allows scaling for the volume of production, reflecting the fact that the cost of a blackout of a particular duration is not the same for industrial users of different sizes. Table 2 below presents estimates of the loss of value-added production for different industries based on national statistics and recently updated by the Finnish Energy Authority (2015) using values reported in Mäkinen et al. (2009). In the table, VoLL €/kW is the value of production lost due to a disruption (of any duration) in the supply of electricity and €/kWh the value of production lost based on the entire duration of the blackout.

Statistics Finland (2014a) gathers statistics about the use of energy in different sectors. Within the sectors, companies are classified based on their turnover. For example, in the agricultural sector, 99% of the companies are small, having turnovers of less than €100,000. The average energy consumption for such a company is 20,000 kWh per year, or 2.3kWh/h, and the average power is 25 kW. The power and electricity use have also been calculated for the chemical, paper, metal and mining sectors. Only companies with a turnover less than €400,000 have been included in the above figures. Large facilities, whose turnover and consumption are greater, obtain their electricity directly from the high-voltage grid, which is a weather resilient.

Table 1 Output of the linear regression model

	Estimate	Std. Error	t-value
Intercept	9.8702	5.3269	1.853
Length in hours	10.1395	0.3138	32.314

Table 2 VoLL for Finnish industrial users (Energy Authority 2015) and agriculture (Honkapuro 2006)

Sector	VoLL €/kW	VoLL €/kWh (€2015)
Mining	0.44	0.27
Paper and wood	2.60	0.23
Chemical industry	2.40	2.00
Metal industry	2.02	0.98
Agriculture	0.45	9.38

Estimation of Benefits from Reclaiming Bare Forest Land

Underground cabling brings ecosystem benefits. For instance, one company in our data set estimates that in 2016, 800 ha of what had been mainly forested land became made available when overhead lines were removed, and estimates that in the future the figure will be 1000 ha annually (Caruna 31.10.2017). This would correspond to approximately 2000 ha/year in our study area. To quantify these benefits, we use the figures from Tahvonen et al. (2013), who calculated the value of cleared forest land assuming optimal rotation periods. For an optimal land type in the study area, the value at a discount rate of 3% corresponds to 447€ per hectare; when the rate approaches 5%, the value per hectare approaches zero. For a less optimal land type, the corresponding values are very low, 38€ and − 177€. We assume that in the case of negative values, the land will not be used for forestry; a minimum value of 0 and a maximum value of €447 per hectare is used in the Monte Carlo simulation. These values are already discounted for future profits. The benefits will be realised during the renewal phase of the network, a period spanning 15 years.

The length of power lines will increase due to their relocation from forest to roadsides. It has been estimated that in rural areas the increase in length will be 1.1 times for the low-voltage network and 1.2 times for the medium-voltage network. (personal communication, Karvonen 2018). In the Monte-Carlo simulation, we specify a distribution with a range between 1.0 and 1.2 for the low-voltage network and between 1.1 and 1.3 for the medium-voltage network.

Estimation of Costs

As noted above, compliance with the requirements of the Act requires a high level of investment in the case of both the low- and medium-voltage networks (Partanen et al. 2012). In particular, a significant proportion of the electricity network laid underground. To quantify the costs, we need to know the i) current extent of underground cabling, ii) required extent of underground cabling and iii) length of the network in rural and urban areas and iv) costs of underground as opposed to overhead lines. Partanen et al. (2012) present estimates of the required level of underground cabling in rural areas, where underground cabling of medium- and low-voltage networks are partial substitutes for each other; that is, by increasing the proportion of underground cabling in one network, the proportion can be decreased in the other, but at a diminishing rate.

Figure 2 illustrates the requirements for underground cabling rates in rural areas for the electricity distribution companies included in the analysis of Partanen et al. (2012). The set of companies is not the same as that in our analysis, but the same cabling rates are assumed to apply. Each coloured line represents the required rate for one company, and the dots describe the current extent of underground cabling. For instance, if the cabling rate for the low-voltage

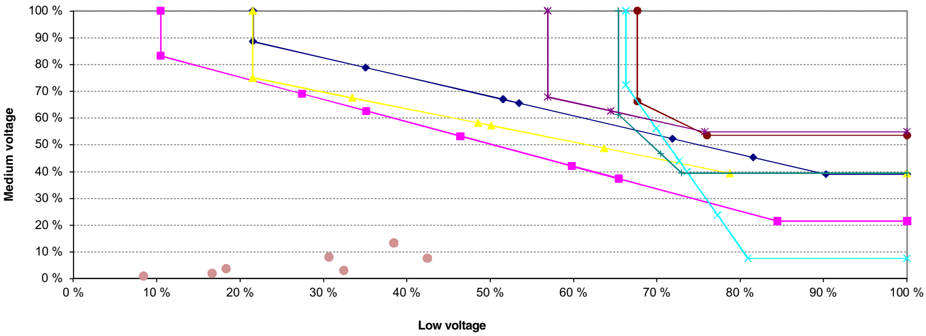

Fig. 2 Required level of underground cabling for seven electricity companies in rural areas (graph from Partanen et al. 2012)

network is 35–45%, the rate for the medium voltage network must extend to 50–80%; if the cabling rate of the low-voltage network is 70–90%, the rate of the medium-voltage network needs to be between 20 and 60%, depending on the company. These rates would make it possible to meet the 36-h blackout limit. In urban areas, a 100% underground cabling rate is required for both the low- and medium-voltage networks to ensure compliance with the 6-h limit.

In our analysis, we assume that the companies choose the level of cabling that i) meets the requirements and ii) is the cheapest to produce. In other words, they comply with the Act but in a cost-efficient manner.

Data

To evaluate the increased reliability of the electricity grid, we need data on the current and expected blackouts in the analysed region. In Finland, electricity distribution companies are required to collect blackout statistics. The annual statistics are published by the Finnish Energy, an umbrella organisation of the energy companies in Finland, but the data are available only as an aggregate for all 80 companies operating in the country. To overcome this obstacle, we purchased raw data for eight companies from a private consultancy firm that analyses data for Finnish Energy (ENEASE 2016). This data set is also aggregated such that no individual company can be identified. However, we know the companies in the set and are able to analyse their network status. In addition to blackout data, we need the rate of underground cabling and customer information, which are provided by the Energy Authority (2015). Significantly, the operating areas of the companies form a single, representative region for which we can also analyse the weather and climatic conditions now and in the future.

The region encompasses Pirkanmaa region in south-western Finland as well as surrounding areas served by the electricity distribution companies operating in Pirkanmaa. The sample covers over 30% of the consumers in Finland, has both rural and urban areas in approximately the same proportion as the rest of Finland, and contains both large and small companies. Some of the companies are very small and local. Table 3 shows the distribution of consumers between different industries and household consumers among the eight companies.

For the costs, we need to know i) the present rate of underground cabling, ii) the length of both the low- and medium-voltage networks for all the operators, divided between urban and rural users, and iii) the costs of underground cabling for a unit of (km) of network.

Table 3 Users of the electricity grids in the study area

Division of different user groups	Agriculture	Industry	Services and construction	Households	Total
Share %	0.6	0.6	0.6	98.2	100
Amount	6600	6600	6600	080200	100,000

The current level of cabling is public knowledge, provided in the annual reports of electricity companies. (Energy Authority 2015). These are shown for the eight companies in the area in Figure 3. The y-axis marks the current rate of medium-voltage underground cabling, and the x-axis that of low-voltage underground cabling.

In the areas studied, the total length of the medium voltage network is 52,528 km, and of the low-voltage network 99,708 km. (Energy Authority 2015).

Lastly, we need to know the average costs for both the low- and medium-voltage networks. Partanen et al. (2012) estimate for the medium-voltage network that underground cabling is two times more expensive than traditional overhead power lines, the costs being 61,700€/km compared to 28,800–32,200€/km. Based on the data from the Energy Authority (2011, 2014, 2016), a substantial decrease in the costs has occurred only in the case of the heaviest cables; the costs of other types and the average costs have remained almost constant. No substantial learning effects and resulting decrease in costs are expected, as thousands of kilometres of underground cables have already been installed.

For the low-voltage network, the difference in the costs between underground cabling and overhead lines in rural areas is smaller, approximately 3000€/km, the figures being 21,000 €/km and 18,000 €/km respectively. Data collected from the electricity grid companies indicate that in urban areas the costs are again nearly twice as high for underground cabling, or 34,000 €/km compared to 18,000€/km (Energy Authority 2016). The difference is explained by the more expensive digging costs in urban areas.

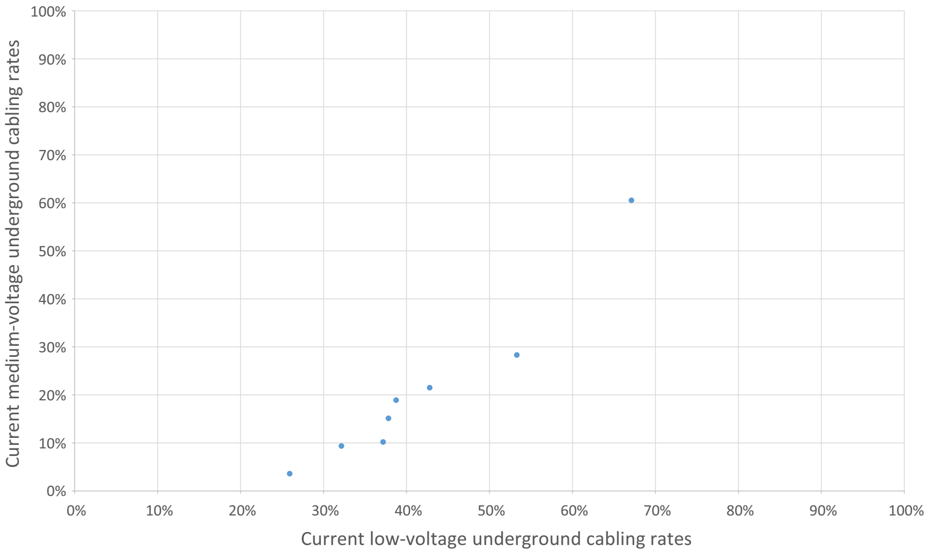

Fig. 3 The current state of the electricity network (Data from Energy Authority 2015)

The blackout data cover the 10-year period from 2005 to 2014, which includes the years 2011 and 2013 that saw storms causing long blackouts in the study area. The return period for such storms cannot be estimated with current knowledge, as gust winds cause most of the major damage to trees - and most blackouts – but the measurement period for such winds has not been not long enough to produce return period estimates for a particular location.

Significantly, both the 2011 and 2013 storms occurred when the soil had yet to freeze. When the depth of soil frost extends less than 20 cm, trees are not properly anchored to the ground and are thus very susceptible to uprooting (Gregow et al. 2011). As we are interested in the benefits of improving the reliability of the electricity grid in the future (time span 0–60 years), we have to consider the effects of climate change on weather phenomena, soil conditions and vulnerability of the sites affected.

First, we consider the current climatic conditions in the area of concern, that is, Pirkanmaa and surrounding areas, meaning southern, southwestern and central Finland. The current blackout risk can be calculated based on the 2005–2014 time series, which represents the degree of variability in the Finnish climate and the distribution of blackouts between years well (Figure 2). For the future climate, we first take a single-parameter approach. For extreme winds, the model estimates from the EU FP7 project Rain (Groenemeijer et al. 2016) show that extreme winds with an annual exceedance probability of 2% in 1971–2000 will have a probability of 2.5% in 2021–2050 over southern and southwestern Finland. For 2021–2050, there is not much difference between different climate scenarios. From 2071 onwards, climate scenarios have a much greater impact on the annual high wind gust probabilities, but this falls largely out of the scope of our time frame. Annual blizzard probability is decreasing in southern Finland according to all climate scenarios. We can conclude that changes in gust wind or blizzards will not in themselves increase the risk of blackouts. An additional risk to the electricity grid to consider, however, is crown snow load, which is projected to increase in major parts of the country under all climate scenarios and time periods. However, the model results are not statistically significant at the 95% level except for the high-emission scenario RCP8.5 in 2071–2100 in southern Finland, where the results indicate a decreasing risk. (Groenemeijer et al. 2016).

Secondly, we assess the risk induced by climate change and its impact on soil frost (Gregow et al. 2011). These results suggest an increase in the risk of trees being uprooted, even if changes in the wind speeds do not occur. Gregow et al. (2011) indicates that the number of days when tree anchorage is poor will increase will from around 95 (1971–2000) to 185 days (2040–2065) in southern Finland; in other words, the risk of uprooting will nearly double. In central Finland, the corresponding numbers range from 90 to 125 days, implying a 40% increase in risk. However, we remain cautious in using these estimates, the increased risk has already been, to some extent, realised in our data due to the major storms in autumn and winter 2011 and 2013, which occurred with little or no soil frost.

Thus, we combine the increasing soil frost risk with the concurrent occurrence of strong winds and snow loads to describe the storm impact risk. As presented in Gregow et al. (2011 pp.48, Table 6), the risk of uprooting in the spruce-dominated areas in southern Finland will increase by 18% by 2046–2065 when using a SREX climate scenario A1B (Nakicenovic et al. 2000). This corresponds to RCP6.5 or RCP8.5 (Rogelj et al. 2012), depending on the period in question. In Jyväskylä, which reflects the conditions in central Finland, the projected increase is 13%. While these estimates do not include changes in tree species or forest management by 2050, they do give an indication of the economic risk lying ahead in the spruce-dominated regions of southern and central Finland.

In our analysis, we combine this information with the current risk of weather-induced blackouts. The low-end estimate of the future blackout estimate is based on the low-emission scenario, in which the conditions that led to blackouts in 2005–2014 do not change. In the medium- to high-end estimate, we use the risk level indicated by the high-emission scenarios, leading to a 13% to 18% increase in risk by2045. We assume a linear increase in the risk and extrapolate the increase for the remaining period 2045–2075. This leads to an asymmetric distribution for the annual increase in the risk ranging from 0 to 0.6%.

Results

In a cost-benefit analysis, the timing of both the benefits and costs needs to be analysed and discounted to present value. This requires numerical parameter values, which we have obtained from various sources to analyse the costs and benefits as well as the uncertainties, in particular those affecting the benefits. Additional parameters affecting the uncertainty regarding future benefits are the rates of urban and rural population growth. Most underground cabling will be done in rural areas, but with Finland still undergoing rapid urbanisation this might affect the future benefits of the investment.

Benefits

The average annual number of weather-related blackouts was 34,360 in the study area, affecting on average 107 customers. As an aggregate, the consumers faced approximately 3,642,000 blackouts annually. The average length of a blackout was 3 h 20 min. Figure 4 shows the yearly number of blackouts.

We calculate the benefits by assuming that the requirements of the Act are achieved, thus assuming that the electricity network is upgraded according to the requirements of the Act. We divide the household users into urban and rural users (Statistics Finland 2016). In urban areas, we assume that no weather-related blackouts will occur as the underground cabling rate will be increased to 100%. This results in annual benefits of 4.7–49 million € (with mean 19.9 million €). In rural areas, we assume that the blackout frequency will be halved (as about 50% more of

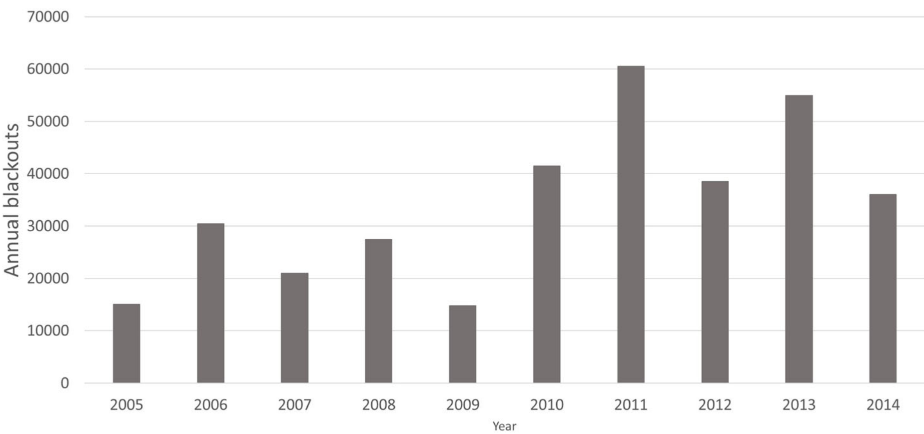

Fig. 4 Weather related blackouts in the study area in 2005–2014

the network will be laid underground) and that no blackouts longer than 36 h will occur. This results in annual benefits of 6.8–70.9 million €. The wide range in both cases is due to the high disparity between the WTP figures reported in the literature. However, the triangular distribution fitted to the range of WTP figures has more probability mass for the values closer to the mean. The benefits are reported in 2015 euros.

For commercial users, we use the VoLL values shown in Table 2. Complementing these, we have collected data on a typical company in each sector and its power and annual electricity use (Statistics Finland 2017). As there are no data on the exact proportions of urban and rural industries, we use the more conservative assumption that the frequency of the blackouts will be halved. The projected benefits for each sector are shown in Table 4. Each sector included contains different subsectors, such as the food industry, wood industry and support services for mining, but as yet there is no VoLL available for sub-sectors separately.

Based on our analysis, the commercial benefits account for some 5% of the total benefits. In the international literature, the total damage costs to industry from blackouts is estimated at around 10% (LaCommare and Joseph 2004). The difference stems from our case as we have taken into account only the small and medium sized industries. In Finland, large companies and industrial facilities are connected to the high voltage network and are outside the scope of this analysis.

Costs

In urban areas, the rate of underground cabling for both the low- and medium- voltage networks must be 100% to meet the requirements of the Act. The current rate for the low-voltage network is around 70%, and for the medium-voltage network 50–60%. (Energy Authority 2015; Finnish Energy 2014). The investment cost for the former is 190–218 million € and for the latter 160–182 million €. For both networks, we further assume that 50% would have to be renewed in any case as part of scheduled maintenance, and 50% would have to be laid underground prematurely. (Partanen et al. 2012).

The underground cabling rates for low- and medium-voltage power lines are partial substitutes in rural areas: increasing the rate in one network could lead to a decrease in the rate required in the other. Underground cabling of the low-voltage network is much cheaper, whereby the most cost-efficient approach is to increase the proportion of underground cabling until it no longer compensates the lower rate in the medium-voltage network. This rate (Partanen et al. 2012; Figure 1) is around 80%. Thus, we assume that in rural areas the underground cabling rate of the low-voltage network will be 80%. The required rate for the

Table 4 Benefits for commercial users

	Chemical industry	Wood and Paper industry	Metal industry	Mining	Agriculture
Number of firms	600	300	1500	150	5450
Number of blackouts / year / firm	3.3	3.3	3.3	3.3	3.3
Length of blackouts / blackout (hours)	3.37	3.37	3.37	3.37	3.37
Annual damage / firm (2015€)	2090	1770	1560	350	110
Annual damage, sector (1000 2015€)	1260	530	2300	50	600
Annual benefit, sector (1000 2015€)	630	270	1150	25	300
Uncertainty range (1000 2015€)	410–840	180–360	770–1560	17–34	200–400

medium-voltage network becomes 20–50% (Partanen et al. 2012; Figure 1), leaving a high uncertainty range. An additional consideration is that the length of the electricity network is assumed to increase, as noted earlier (personal communication, Karvonen 2018). Ultimately, the total cost of meeting the requirements of the Act in rural areas will be 570–1460 million €. The wide range is due to the uncertainty in the required underground cabling rate, which depends on other measures to improve the network. A second source of uncertainty is the increase in the length of the low-voltage and medium-voltage networks when cables are removed from forested land and relocated to roadsides.

Parameter Values

Consumers of electricity obtain the benefits as soon as the investments have occurred and receive the benefits as long as the underground cables are used. For the distribution companies the investment costs are incurred immediately, but for consumers the cost is carried in keeping with the write-off schedule (typically a 30-year straight line-depreciation) and the capital cost of the investment. Consequently, the consumer benefits must exceed at least the weighted average cost of capital (WACC). In 2014, the WACC for electricity networks was 3.2–4.5%. (Äijälä et al. 2014; Ernst and Young 2014) but the cost of external financing has since decreased by 0.5–1% (Bloomberg 2016). For the low end of the discount rate, we use 3%. For the expected value, we use the average 12-month Euribor rate (since the euro area was established and Finland joined it in 2002) plus the current rate; for the high end, we use the highest Euribor rate plus the current cost of borrowed capital. It should be noted that economists (Weitzman 2001) recommend using a time-declining discount rate; in the present case, however, the benefits should be discounted by the cost of capital, as this will also be borne directly by the consumers. In estimating rural and urban population trends, we use projections calculated by the United Nations for Finland. WTP values were derived in section 3.2.1. The costs depend on the required underground cabling rates, as explained in section 3.2.3. Table 5 shows the ranges for the parameter values and their source.

Monte Carlo Analysis and Net Present Value

We ran a Monte-Carlo simulation with the above parameter values and distributions using the Palisade @Risk for Risk Analysis (2018) add-in to Microsoft Excel statistical software. The simulation was run 1,000,000 times. The NPV of the benefits was estimated separately for improvements in the urban and rural networks. Figure 5 depicts the resulting distribution for urban areas. NPV is positive at the 95% significance level. The mean of the NPV distribution is 158 million euros. Of the variance in the NPV, the discount factor explains 86.1%; costs, 1%; WTP, 12.5%; and the urban growth rate, 0.4%.

Figure 6 shows the corresponding distribution for rural areas. The mean NPV is −374 million euros. There is a 96.2% probability that the NPV is negative in rural areas. In a noteworthy difference compared to urban areas, in rural areas the uncertainty in the costs of improving the network has a much larger effect on the variance of the NPV. This uncertainty explains 73.8% of the variance, while the discount factor explains only 21.6%. Other factors explaining the variance include the uncertainty in the true value of WTP (4.3%) and the decrease in the rural population (0.3%).

To summarise, the expected NPV in urban areas is 158 million €, and in rural areas −374 million €. The expected benefits for industrial and agricultural users are 110 million €. To

Table 5 Parameter values, their range and distribution used in the Monte Carlo Analysis

Parameter	Min	Max	Mean	Distribution	Comment	Reference
Discount rate	0.03	0.084	0.048	Asymmetric triangular	Cost of external funding (0.03) + Euribor rate	Äijälä et al. (2014); Ernst and Young (2014); Bloomberg (2016); ECB (2018)
Rate of change of urban population	0.0017	0.004	0.0029	Uniform		UN (2014)
Rate of rural population	−0.011	−0.0073	−0.009	Uniform		UN (2014)
WTP (standardised per hour)	1.5€	15.6€	6.3€	Asymmetric triangular	See section 3.2.1.	Silvast (2005); Matschoss (2014); London Economics (2013)
Costs urban	350	400	375	Symmetric triangular	See section 3.2.2.	Own calculations
Costs rural	570	1460	850	Symmetric Triangular	Depending on the required cabling share; See section 3.2.2.	Own calculations
Value of forest land	0	447	223.5	Uniform	See section	Tahvonen et al. (2013)

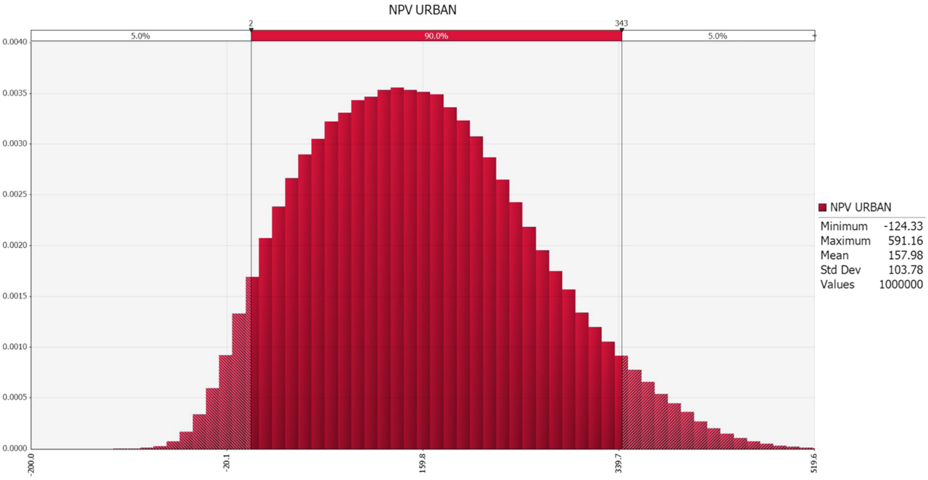

Fig. 5 The distribution of NPV for the urban areas

avoid double-counting, as the costs are already taken into account in the urban and rural analysis, the 110 million euros are added to the aggregate NPV, resulting in total expected NPV of −106 million euros.

The division of NPV between urban and rural areas only refers to the spatial component of the benefits and costs, not to the relative proportion of the investment costs ultimately borne by urban and rural consumers. In fact, if the electricity price increase is spatially uniform, urban customers (85% of the population) will bear most of the total cost (85% assuming uniform electricity use and prices), while the majority of the benefits will go to the rural areas (expectation 40% vs. 60%). However, if an electricity company operates only in a rural area, rural customers will pay all the costs, most likely resulting in greater rate increases than the customers are willing to pay. Clearly, at the margin, in rural areas the costs are higher than the benefits.

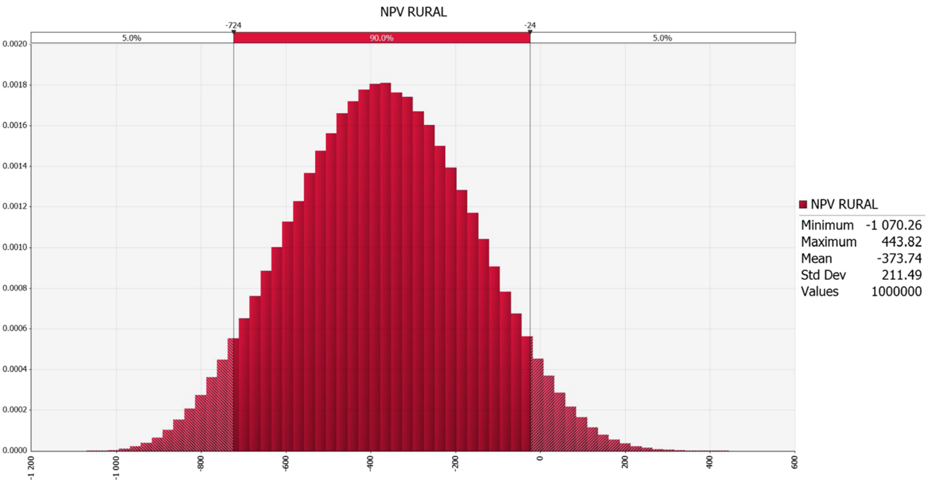

Fig. 6 The distribution of NPV for urban areas

To further analyse the spatial distribution of the benefits and costs, we can divide electricity grid companies into three different categories, examples of which exist can be found in our data: 1) those operating only in rural areas, 2) those operating in both rural and urban areas and 3) those operating only in urban areas. The distribution of benefits and costs differs between these types. All three company types can be found at national level: of the 80 electricity distribution companies in Finland, the 15 largest supply electricity to 70% of the population. Two of the three largest suppliers have rural as well as urban customers. There are also companies that operate only at the scale of a rural municipality. (Finnish Energy 2017).

For companies in category 1, costs are expected to be higher than benefits for the customers. In the case of those in category 2, customers in rural areas extract benefits from the urban customers and may become beneficiaries depending on the distribution of rural and urban customers. With companies in category 3, the NPV is positive at the 95% significance level, and the customers benefit from the requirements of the Act.

In section 2, we introduced the concept of robust adaptation, described in terms of five criteria (Hallegatte et al. 2009). Of these, the Act only fulfils the criterion of no-regret measures, as it clearly creates benefits even in the absence of climate change. However, the Act is not easily retro-fitted; it does not increase safety margins at a low cost; it cannot be classified as a soft measure inasmuch as it results in major investment costs; and the time horizon of the measure is long. Finally, synergies with climate change mitigation efforts are unknown.

Public Reaction

The requirements in the 2013 Electricity Market Act led to major price increases in electricity transmission and an ensuing public outcry over the situation. This following account of these events is based on two sources: the official public releases of one of the distribution companies most seriously affected by the public reaction, and the press releases of the office of the Finnish Consumer Ombudsman. No media reports have been used. The situation can be understood from the press release of 4 February 2016 by the company most heavily affected by the public reaction: “Caruna regrets the distress caused to its customers after having to come to a solution on price increases, due to the large-scale requirement for improvement. The company has advised its customers regarding the network improvement measures required by the Electricity Market Act (Electricity Market Act 588/2013), as well as the price increases connected with them. The price increases have resulted in a large number of objections from citizens as well as in considerable media attention” (Caruna 4.2.2016). The situation began in early 2016, when major price increases were announced by the company, the largest distribution company in Finland. On 3 February 2016, the Consumer Ombudsman released a statement saying that it considered the price hikes excessive from consumers’ point of view (KKV 3.2.2016). The Ombudsman further stated that the price increases were unreasonable because electricity is considered a necessity good, and with the company having a regional monopoly, consumers cannot change their supplier. Negotiations with the company started. The outcome, reached towards the end of 2016, is summed up in the following statement: “Caruna will reduce its fixed basic prices for electricity transmission by 25 per cent for all customers and both of its network companies for the next 12 months. This compensation will also balance the price increase in 2017. Furthermore, Caruna has given a commitment that it will not implement new price increases in 2017.” The Competition and Consumer Authority even considered bringing a class action suit against Caruna (KKV 18.2.2016). This procedure has never been used in

Finland despite an Act providing for it being on the books since 2007 (Class Action Act 13.4.2007/444).

On 25 August 2017, the 2013 Electricity Market Act was amended to incorporate regulation against price increases by transmission companies. In principle, a cap of 15% has been imposed on increases in transmission and distribution prices over a one-year period. (Amendment to the Elecricity Market Act 590/2017).

Notwithstanding, in 2018 Caruna and several other companies implemented another series of price increases, prompting the government to initiate an official investigation into the reasons for the price hikes (TEM 28.5.2018).

Discussion

The impacts of the 2013 Electricity Market Act were evaluated from many different angles (Partanen et al. 2006; Partanen et al. 2012; Government Proposal HE 20/2013) before the Act was passed and enacted, but no CBA such as that presented here was conducted. Before the Act came into force, Partanen et al. (2006, 2012) pointed out that a previously suggested 24-h limit for rural blackouts would be economically inefficient and a 36-h limit would be economically more viable. Our analysis indicates that the 36-h limit for the rural network is still too restrictive in some cases, as the benefits for the rural population are not high enough to justify the costs brought by the increased price of electricity distribution. We must note, however, that according to the ministry tasked with drafting the Act, the legislation had goals apart from reducing the impacts of extreme weather. Principal among these were the need to address the maintenance backlog and to ensure the security of supply throughout the country. The suboptimality we have described here is to be understood in strictly economic terms. Indeed, we acknowledge that a policy may be informed by other than economic objectives, such as national security, as noted above.

In Europe, we have seen a significant increase in damages to forests that have partly been caused by forest management practices that have favoured plantation of tree species (Norway spruce) that are easily uprooted (Gregow et al. 2017). By better forest management practices, the damages could have been less severe although not avoidable (Suvanto et al. 2016; Pukkala et al. 2016), whereby compliance with the Act cannot be guaranteed by these measures alone. However, the duration of blackouts in rural areas could be reduced with appropriate forest management, and the costs of doing so would be substantially smaller than the costs of laying underground cables. The economic efficiency of such measures – or less strict requirements for rural areas - should have been compared to underground cabling. The present analysis has evaluated only the 24- and the 36-h limits from an economic perspective. An additional consideration is that if the renewal of the network had a less strict deadline, overhead power lines could be used until the end of their technical lifecycle, and then be replaced by the underground cables. This would substantially decrease the total costs resulting from the requirements of the Act.

One limitation of our analysis is that the benefits may rise if WTP for avoiding of blackouts increases in the future, for instance due to an increasing dependence of households on electricity. Increasing income levels could also have an effect. In 2015, disposable income had not increased in the past decade (Statistics Finland 2014b); however, since 2015 there has been a slight increase in mean, but not median, disposable income. Moreover, as the income elasticity of WTP is not reported in the original studies, scaling up the WTP figures would be questionable. In addition, many electronic appliances now come with a battery. As battery technology improves, WTP values may well decrease. On balance, we feel that the current WTP range is wide enough to cover the uncertainty in consumers' WTP and thus have not considered any increase or decrease in the WTP.

As mentioned in Section 3.1, CBA should account for distortionary effects, primarily those related to labour supply resulting from changes in household preferences between labour and leisure. A distortionary effect means that due to income taxation the labour supply is not at its optimal level in the equilibrium (Johansson-Stenman 2005). If a proposed project increases the labour supply, its distortionary effects are positive, and if it decreases the supply, the effects are negative. There is little empirical evidence on the effect of changing energy prices on the labour supply; only the effects of demand have been studied rigorously (e.g. Asafu-Adjaye 2000; Papapetrou 2001). In our analysis, potential labour supply effects are more important, as the costs are mainly borne by household users; it is difficult to say anything certain about these or even about the direction of a possible change.

Distributional effects can be studied by comparing the benefits received by different income groups and assigning different social welfare weights to different groups, so that lower income groups are assigned a higher weight (e.g. Adler 2013), or by reporting the distributional issues qualitatively in the analysis (Nyborg 2014). In this analysis, it is possible to divide the individuals into urban and rural populations, as the benefits are distributed unevenly among the two groups. However, we cannot use individual benefit-income pairs as a basis for calculating distributional weights, and thus only report distributional effects qualitatively.

An analysis by the Bank of Finland (Mäki-Fränti 2016) has indicated that the income differences between regions in Finland are small. The five least urbanised regions have an average income 77% of those with the highest urbanisation rate (Mäki-Fränti 2016). In the analysis, we have used average VoLL figures for households for all different regions. Averages could be adjusted regionally to take into account the effect of income on VoLL. None of the primary literature studies report the income elasticity of VoLL, but Carlsson et al. (2011) report a positive income effect for the reported VoLL values. This would mean an even lower NPV for the rural case, but an improved NPV for the urban case. The differences in the production per capita in the rural and urban regions are much higher, but taxes and transfers decrease the income gap between urban and rural population. However, if distributional concerns are taken into account, both the benefits and the costs of the rural population should be assigned slightly higher weights than those of the urban population, making the rural case more negative.

Of greatest concern are those rural areas that have their own distribution company. In such cases, the rural population needs to pay a higher price for the increase in the electricity price as compared to its WTP. Even if less urbanised regions are not that poor on average, the poorest municipalities are located in the rural areas. Moreover, the share of low-income households is much higher in rural areas than in urban areas, around 4% compared to around 2%. (Statistics Finland 2018). Electricity companies operating solely in rural areas may find it difficult to fully recoup their investment. They companies may consider not investing in underground cabling, but rather in improving their forest management practices around power lines. However, there is no guarantee that such measures will increase the reliability of the network to the standard required by the Act. The independence of such companies may be jeopardised, possibly resulting in mergers.

The literature (Onuma et al. 2016; Onuma et al. 2017a, 2017b) shows that CCA and DRR are often dynamic processes, as both individuals and societies learn from past disasters and increase their preparedness. In our case, the high impact storms in 2006, 2010 and 2011 clearly had an impact on public policy, and these experiences were part of the knowledge base informing the regulation. Our analysis shows that this dynamic process can also lead to an overreaction from the point of view of economic optimality.

Conclusions and Implications

Over-adaptation to the impacts of extreme weather and climate change has rarely been discussed in the literature. The literature is rich in examples where CCA and DRR measures are reported to be economically efficient, whereas counter-examples are few. We claim that this is due partly to reporting practices, and partly to imprecise definitions of efficient adaptation.

As a case study, we undertook a CBA of the 2013 Finnish Electricity Market Act, which imposes strict requirements on electricity distribution companies to prevent black-outs in their grid. Our results indicate that in urban areas the public policy and the required investment are economically efficient. However, in rural areas, the costs of the required investments exceed their economic benefits, indicating that the optimal require-ments would have been somewhere between the old practices and the new. Depending on the operating area of a given electricity distribution company, the present requirements will result either in urban customers paying for the improved well-being of rural customers or rural customers having to bear the high cost of improving network reliability on their own. This cost is expected to be higher than the NPV for the improvement. Our results indicate that the present policy may be an overreaction to an existing problem: it seems that at some "quantity" (urban requirements), NPV is strictly positive, whereas at another level of service provision (rural requirements), NPV is negative.

Our case study indicates that over-adaptation is a relevant concept meriting consideration the CCA and DRR literature. Our case also shows that when assessing the success of public regulation and measures aiming at reducing the risk of extreme weather events and climate change, public opinion and potential and perceived negative effects on the public should be considered. The population affected by the impacts may not accept the implementation of otherwise effective DRR and CCA measures. This applies particularly when there is a potential mismatch between societal and individual preferences. Furthermore, the WTP of the people affected should be carefully evaluated prior to any policy change, as the WTP obtained in surveys may prove to be different from the WTP of the affected population. All in all, from the point of view of good governance, the significance of identifying over-adaptation is that it adds to our understanding of strong popular inclinations to avoid risks relating to the availability of an essential good, such as energy. Popular concerns may affect decision-making such that the resulting actions clash with the equally important objective of providing that good being at an affordable price.

Reducing the impacts of extreme weather events and adapting to climate change are challenging tasks given the many climatic, societal and political uncertainties. Despite these uncertainties, designing and implementing policy instruments and concrete measures is highly important due to the intensifying threat of climate change. Economic efficiency of the envisaged measures is one key criterion to be used in designing the instruments; however, the challenge for policy makers is to design instruments that are accepted by the public.

System flexibility is essential in ensuring that the net benefits of a given project do not fall in the range of over-adaptation. This study has shown that CBAs evaluating potential CCA and DRR measures should better address suboptimalities.

Appendix

Milestones and events	Time and reference	Notes
A government report by an investigator" Improving the reliability of electricity network"	2002 / KTM 18/2002	Early report including a discussion on the urban requirement of a maximum 6-h blackout.
A government report" The compensation costs for blackouts"	2002 / KTM 11/2002	Early report including discussion on the compensation that customers are entitled in case of blackouts.
A working group named ""Preventing disruptions in the electricity network and improvement of the operational goals" report: "Improving the reliability of the supply of electricity"	KTM 19.12.2006	The report included discussion on the blackouts statistics; historical development of blackouts; international comparison; discussion on the maximum allowed blackout periods; discussion and very crude estimates on the costs and benefits of increasing the underground cabling rates of low- and medium-voltage networks
A report by Technical University of Lappeenranta "	Partanen et al. (2006)	The report included a discussion as well as calculations of the benefits and costs of different maximum allowable blackout durations (6-10 h total blackout duration in one year under normal conditions, 24-48 h during major disturbances); It was concluded that the maximum of 6–10 h cumulative duration per customer is reasonable in normal conditions, but setting a strict time limit in case of major disturbances – such as storms – cannot be justified from an economic perspective; The report also mentions that for some (rural) electricity companies, there could be less strict deadlines.
A legislative proposal by the Ministry of Economic Affairs and Employment of Finland (TEM) "Measures to improve the reliability of electricity supply and decrease the impacts of blackouts"	TEM 16.3.2012	Included the final (acceptability) requirements of at maximum 6-h blackouts in urban areas, and either a 24- or a 36-h maximum duration in rural areas
An impact analysis report of the legislative proposal of TEM, by Technical University of Lappeenranta "An impact analysis of the measures to improve the reliability of electricity supply and decrease the impacts of blackouts"	Partanen et al. (2012)	In this report is was concluded that the 24-h deadline for the maximum blackout periods in rural areas is too strict, and the 36 h deadline is more favourable from an economic point of view. Longer maximum blackout periods were not considered, as the proposal did not include them.
Government proposal	HE 20/2013	A proposal for the new Electricity Market Act.

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III

EJTIR

Issue 16(1), 2016
pp. 150-173
ISSN: 1567-7141
tlo.tbm.tudelft.nl/ejtir

Innovations in weather services as a crucial building block for climate change adaptation in road transport

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The road transport sector is facing rising uncertainties in planning and operations due to climate change induced changes in weather variability and extreme events. However, because of the high level of uncertainty related to the future climate, adaptation measures should be robust so as to retain the option value of the portfolio of measures. As an example of such a measure, this paper evaluates how foreseen innovations in weather services could reduce weather sensitivity and, consequently reduce the negative effects of climate change in the sector. The study is based on a theoretical framework on climate change adaptation and valuation of weather and climate services using the Weather Service Chain Analysis. We apply these frameworks to the road transport sector with a special emphasis on drivers' decision making before and during a trip. We show that improved weather information, including more accurate weather forecasts, new applications and information dissemination channels can decrease the vulnerability of the mode to projected shifts in extreme weather patterns due to climate change.

Keywords: *Adaptation, Climate Change, Information, Innovation, Road transport, Weather Service*

1. Introduction

1.1 Climate change and the transport sector

The link between the transport sector and climate change is twofold. Mitigation of climate change, for instance the reduction of greenhouse gas emissions from transport activities, has received plenty of attention due to its significant contribution to the global emissions (IPCC, 2014a). However, the transport sector is not only a contributor to climate change, but in all likelihood will be notably affected by its consequences (Hallegatte, 2009; IPCC, 2014b; Love et al., 2010).

The report by the Intergovernmental Panel on Climate Change entitled *Impacts, Adaptation and Vulnerability* reviews the expected direct and indirect impacts of climate change on transport (IPCC, 2014b). The impacts are not uniform, and depend, for instance, on the geographic area considered, transport mode, time frame and factors such as technological development and economic growth (IPCC, 2014b; Koetse and Rietveld, 2009; Michaelides et al., 2014; Nokkala et al.,

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2012; MMM, 2012). Koetse and Rietveld (2009) suggest that the changing weather variability and extreme weather events may be the impacts of most concern for the transport sector.

Weather related disturbances, existing in the current climate, already affect the transport sector. In the aviation sector, the main weather related costs are related to both primary and network delays, cancellations and diversion (e.g. Cook et al., 2004). For road transport, weather related accident costs dominate other weather related costs (Nokkala et al., 2012). With regards to rail transport, extreme weather has an effect on operating efficiency, physical infrastructure and the safe passage of freight and people (Rossetti, 2007). For maritime transport, weather has an effect on stability, journey time, safety of the cargo and vessel, fuel efficiency and admissible load factor (Nurmi et al., 2012). Additionally, transport modes do not operate in isolation but rather constitute a multi-modal transport network, in which chain events can emerge even if adverse weather directly affects only one mode. Indirect impacts of climate change may stem from for instance changes in agricultural, tourism and production patterns (Koetse and Rietveld, 2009).

The projected effects of climate change on the frequency and intensity of extreme weather events in different regions in Europe still have a significant degree of uncertainty due to their combination with other sources of uncertainty, such as natural variability of the climate, uncertainty in climate and economic modelling and socioeconomic development. The highest level of uncertainty is related to changes in extremes. Nonetheless, with reasonable confidence it is projected that the frequency and intensity of cold waves is will decrease throughout Europe, while the duration and occurrence of heat waves is projected to increase. In particular the projected levels of extreme precipitation and wind speeds in future climates entail higher uncertainty as compared to temperature. Jylhä et al. (2009), nonetheless, find that in northern Europe, extreme downpours may be expected to increase. In principle, extreme winter-weather events (cold spells, blizzards and snowfall) are expected to decrease in most regions of Europe by 2050; an exception is that the frequency of extreme snow storms is projected to slightly increase in Northern Europe. (Vajda et al., 2011; Perkins et al., 2012). In a study on the Alpine region, Rajzak et al. (2013) project that in several areas of the northern Alpine region, the severity of extreme precipitation (snow) in winter time increases, while the frequency might decrease. In other seasons, the tendency is towards reduced frequency and increased intensity in most Alpine regions.

1.2 Climate change adaptation in the transport sector

For the transport sector adaptation to projected changes in extreme weather patterns (Koetse and Rietveld, 2009), while keeping in mind the high uncertainty in climate projections (Vajda et al., 2011), costly adjustment of transport infrastructure is not necessarily the most optimal option (Hallegatte, 2009). In turn, this implies that scenario-based long-term climate information is rarely the key driver behind climate change adaptation (CCA) decisions (Love et al., 2010). Instead, the focus should be on finding strategies and adaptation measres which take into account the changing climate, whilst also addressing the inherent uncertainty related to climate change. To address this issue, robust CCA decisions and strategies, which are insensitive to the uncertainty related to the future climate, have been suggested (Dessai and Hulme, 2007; Hallegatte, 2009).

The provision of weather information can be considered a robust CCA strategy for the transport sector, as weather services are beneficial for road transport in the current climate and with current level of services. However, different processes in nature and society co-exist that shape the future of road transport; climate change is altering weather variability, whilst innovations in weather and climate services and technological development in road transport sector are changing the way services are provided and how the services are used by vehicle drivers, thereby affecting the overall safety of the road transport mode.

The use and value of current weather services in the road transport sector have been studied for instance in Frei et al. (2012), Nurmi et al. (2012) and WIST (2002) (see Section 5). Some research on how innovations, such as intelligent road transport systems (e.g. Innamaa et al., 2012; Ezell, 2010) can be used to increase the function of road transport in the future has been undertaken. Regarding weather services, much of the research has focused on the development of specific technologies to improve these services, such as using vehicles as observation devices (Drobot et al., 2012) or developing new communication channels to reach the drivers (Roine, 2010).

1.3 Aim and objectives

Innovations in weather services and consequent increases in the benefits of weather services have the potential to improve the resilience of the transport sector to the expected adverse impacts of climate change. The aim of this study is to evaluate how potential innovations in weather services can reduce weather sensitivity and, consequentially, decrease the negative effects of climate change in the transport sector, and particularly the road transport sector.

The study focuses on the road transport for two reasons. Firstly, it is the most vulnerable transport mode to extreme weather, at least if assessed in terms of the aggregate costs related to extreme weather events (Nokkala et al., 2012). Approximately 10% of the road accidents can be attributed to extreme weather events (Nurmi et al., 2012) which translates into extreme weather related losses of over 20 billion euros per year in Europe (Nokkala et al., 2012). Secondly, it serves as a good example to illustrate how innovations in the provision and use of weather information can prove to be beneficial for adapting to the changing climate.

The objectives of this paper are to 1) identify and describe the main trends and potential innovations in the provision and use of weather services in the road transport sector (section 4); 2) identify where in the weather service provision value chain these innovations would have an impact on the use of weather information before and during the trip (Section 5); and 3) analyse the expected magnitude of the value of these innovations (Sections 5 and 6).

The overall purpose of this work is to contribute to the understanding of the overall effects of the improved weather service provision on the safety of road transport to improve climate change adaptation in the road transport sector.

2. Weather services to support climate change adaptation in road transport sector

2.1 Climate Change Adaptation

This paper utilises the approach provided in Smit et al. (2000) to systematically specify and characterise CCA. This approach is based upon responding to the following three questions: 1) Adapt to what? 2) Who or what adapts? 3) How does adaptation occur?, which are outlined below.

1. Adapt to what?

The uncertain, and changing, extreme weather patterns are considered to be the most urgent threat to road transport (see Section 1). Direct impacts of climate change will occur due to, for instance:

- changing freeze/thaw cycles, which will affect winter road maintenance costs and accidents rates (Andersson and Chapman, 2011);
- changing precipitation patterns affecting rainfall, flooding, snow and visibility, which may affect the number of road accidents (Jaroszweski and McNamara, 2014; Jaroszweski et al., 2010; Qiu and Nixon, 2008) and congestion (Koetse and Rietveld, 2009);
- increase in the intensity in hot spells which could increase the accident risk due to psychological and physiological effects (Laaidi and Laaidi, 1997); and

- increase in strong winds, which have a potential adverse effect on road safety (Thordarson, 2006).

2. Who or what adapts?

The most suitable adaptation strategies to climate change are defined by the system in question and its characteristics. The system itself and its need to adapt are defined by various determinants, which measure for instance the vulnerability, resilience and adaptive capacity of the system to climate change. In the road transport sector, different responses are required at operational and structural levels. At the operational level, the role of the vehicle driver is prominent, although adaptation at the infrastructure level, for instance relating to traffic flow management, may become necessary as well. Vehicle drivers respond to quickly unfolding extreme weather events with short lead-times by adapting departure time, changing the route, switching travel mode, and by cancelling the trip. To long-term developments, vehicle drivers can respond by adapting their decision on vehicle ownership, by moving residence or changing a default shopping location. (Hensher and Brewer, 2000; Polak and Heertje, 1993)

At the structural level, measures regarding the capacity, location, and technical standards of transport infrastructure are required. The focus of this paper is the use of weather services as a robust adaptation measure; therefore, CCA is not assumed to take place at the system level, but to be implemented at the level of the user, as vehicle drivers are vulnerable to climate change effects due to changes in the extreme weather patterns.

3. How does adaptation occur?

Adaptation can refer to both natural and manmade systems and may entail both autonomous adaptation, in which a system responds to climate change spontaneously, and planned adaptation, in which deliberate adaptation strategies are developed and measures implemented. This is linked to the timing of adaptation, which can happen prior to any impacts (anticipatory), while the impacts are occurring (concurrent) or be reactive and take place only after the impacts have occurred. Furthermore, adaptation to climate change can be either incremental, if the system is changed by merely extending the current practices which are used to adapt to weather events, or transformational, if adaptation entails far reaching changes in the considered system. (Carter et al., 1994; Smit et al., 2000; Kates et al., 2012)

Due to the uncertainty of the extent of climate change in the future climate (Vajda et al., 2011) and the aforementioned impacts, robust (i.e. valid in many scenarios), yet adaptive, adaptation strategies may be a wiser approach as compared to major infrastructure investments (Dessai and Hulme, 2007). This consideration is based on option value theory, for instance "the benefit derived from keeping options open so as to be able to adjust policies in the light of better information" (Ingham et al., 2007) and to avoid sunk costs (Hallegatte, 2009). With regards to robust adaptation strategies, Hallegatte (2009) suggests the following: *No regret* measures which create benefits even in the absence of climate change; *Reversible* measures which are easily retro-fitted if climate change projections turn out to be wrong; *Safety Margin* measures which reduce the vulnerability of the system at a low or no-cost; *Soft* measures which can be institutional or financial; *Reduced time horizon* measures which involve reducing the lifetime of an investment; and strategies which have *Synergies with mitigation.*

A further classification of adaptation measures is proposed in Perrels et al. (2013a). This classification is based on whether the measures are to reduce (1) exposure; (2) vulnerability, or to (3) improve (active) resilience. Improving weather information belongs to the third category. Due to its 'active nature', it blurs the distinction between planned and automatic adaptation, and thereby it may also link incremental and transformational adaptation. As Rotmans and Loorbach (2009) indicate, transformations cannot be fully planned, but can be promoted and facilitated inter alia by enhancing automatic adaptation capabilities through innovations.

This study builds on these definitions and observations and aims to identify to what extent innovations in weather services can help to improve anticipatory, planned adaptation to climate change in the road transport sector, whilst at the same time open up options for more fundamental changes (transitions) in the system. A key element in this respect is the provision and use of weather information so as to enhance well informed decision-making.

Weather information is beneficial for the road transport sector only if successfully used. Therefore, innovations in weather services should focus on the entire weather service chain (including forecasting, information tailoring, media choice, access, comprehension, leeway for response, benefit retention) in order to maximize the leverage of the improvement efforts. (Perrels et al., 2013b)

2.2 Weather Service Chain Analysis

Weather services can be considered a robust, no-regret adaptive CCA measure, as they provide active resilience in current and future climates. For instance, Hallegatte (2009) suggests that early warning systems are a 'no regret', reversible, and soft measure to respond to climate change impacts.

Weather information can be understood as a factor in a decision process aimed at maximizing the value or utility of a considered process or activity. A hypothetical maximum benefit potential of meteorological services can be estimated, assuming that perfect initial information (e.g. perfect weather forecast) is combined with 100% use among end users and 100% effectiveness of their responses. However, the actual level of realised benefits depends on the quality of the information, and the timeliness and ability of the involved users to respond to the information. (Perrels et al., 2013; WMO, 2012)

The actual value of the initial meteorological information stems from the use of the information and the extent to which the end users are able to interpret and use the information and transfer the benefits to other agents. An important aspect in the approximation of the actual level of realised benefits is the information decay in the service chain. Weather Service Chain Analysis (WSCA) (Nurmi et al., 2013) aims at accounting for the inadequacies in the dissemination and use of weather information. The approach describes the decay of the benefit potential based on a decomposition of the information flow, ranging from information generation to benefit realization for the end-user and society as a whole.

This approach has been used extensively in section 5, in which each step (apart from 7 which would require macro-economic analysis) is analysed with regards to how vehicle drivers are able to use and benefit current and improved weather information. WSCA can be used in a semi-quantitative way indicating orders of magnitude of improving potentials per step (which can be related to managerial actions aiming at that step). WSCA can also be used in a more formalized fashion, resulting in estimated fractions, e.g. for the purpose of cost-benefit analysis of a weather service. The seven steps of the WSCA assess the extent to which:

1. Hydro-meteorological information is accurate [accuracy];
2. Information contains appropriate data for a potential end user [appropriateness];
3. The end user has (timely) access to the information [access];
4. The end user adequately understands the information [Understanding];
5. The end user responds to the information to effectively adapt behaviour [responsiveness];
6. Responses actually help to avoid damage or improve operations [response effectiveness];
7. Benefits from adapted action or decision are transferred to other economic agents.

The estimate of the overall effective avoidance share Q can be calculated with the following equation; bearing in mind that the linear structure of the model gives only an approximation of the value decay in each step ($S_1 \ldots S_6$):

$$\mathrm{Q} = \prod_{s=1}^{6} \{S_i\} \tag{1}$$

The weather service market is essentially based on observing and predicting weather and effectively communicating the produced information to users. While this structure remains, in the process of innovation the components of the market undergo changes. The technology develops, enabling improved level of both temporal and spatial accuracy, and meanwhile also the communication channels develop and change. As Bayesian decision-theory suggests, improved level of information only brings incremental value if it has an effect on the decision-making (Katz and Murphy, 1997).

Consequently, we use WSCA in conjunction with decision-analysis by analysing the decision-making process of the vehicle drivers. This approach requires mapping of the following information: (1) relevant decisions for a user (or user group) for which weather information has a differential effect; (2) need to identify what are the relevant future possible events that may occur and the economic consequences of those; (3) how well the different stages of the WSCA are realized at the moment, and (4) which parts of the chain will or should develop in the future to create economic benefits.[7]

3. Methods and data

Semi-structured interviews were performed to identify the trends and potential innovations in the provision and use of weather services and analyse the value of these innovations in the weather service provision value chain. Semi-structured interviews have a planned interview guide, but are open to new topics, as it allows exploring of new areas emerging during the interview (Gillham, 2005). The interview guide used was designed based on the WSCA, described in Section 2.2. Altogether 12 semi-structured interviews were undertaken during the spring of 2013 by the two first authors of this paper.

Out of the 12 interviewees, eight represented a national hydro-meteorological service (NHMS) and were experts on weather and transport, or service or business development. Requests for interviews were sent to several European NHMSs, and interviewees were selected in order to obtain a balanced representation of all aspects of meteorological and climatological development. Furthermore, three experts in the areas of weather observations equipment and related technologies were interviewed. In addition, a winter road maintenance company was interviewed to gain an understanding of the link between weather information and road-users. The winter road maintenance company is one of the two big players in Finland that share regional maintenance contracts. It has an almost identical operational structure to that of many countries, for instance, in Sweden, Norway and Canada. Individual driver behaviour was analysed through literature (Sihvola and Rämä, 2008; Cools and Creemers, 2013).

The purpose of the interviews varied according to the stakeholder category:

- NHMS: to identify the services provided for road transport sector and the main trends in new meteorological services;
- weather forecast model developer (European Centre for Medium-range Weather Forecasts): to determine the expected future capabilities of weather models and their dependence on the investments;

[7] A classical reference for decision analysis approach regarding weather information is Katz and Murphy (1997)

- weather observations equipment supplier: to determine the development of the observation network as an enabler of more spatially accurate weather information;
- expert/professor on information, communication and networking technology: to understand technological development and innovation processes in information and communication technology, particularly related to weather service provision
- Interface between weather service provision and road users: to understand the current use of weather and climate information to ensure safe driving conditions for the vehicle drivers, the need for improved information and how climate change is expected to change the operational environment and data needs.

All interviews were transcribed verbatim and coded and analysed independently by the first two authors of the paper. The interviews were coded with respect to three aspects: 1) who is the target or the user of the innovation in the weather service provision (road maintenance companies, professional drivers and normal vehicle drivers); 2) what type of weather or climate forecasting is the innovation expected to improve (nowcasts[8], short-range weather forecasts [up to 72 hours], medium-range forecasts [up to 10 days], monthly forecasts and seasonal forecasts); and 3) in which step of the WSCA is the innovation considered to be relevant (introduced in section 2.2).

4. Foreseen innovations in weather services

Based on the results of the semi-structured interviews, the overall trends and innovations in meteorological services up to 2030 can be classified into three categories: observation technology, global weather models and information and communication technology (ICT).

4.1 Observation technologies

Observations (either with radar instruments, meteorological satellites or mobile devices) are the starting point of any meteorological work and an important factor behind improved weather forecasts is a dense and reliable observations network. Therefore, innovations in the coverage and reliability of observational instruments are highly significant in determining the future capabilities of weather forecasts.

The current state-of-the-art radar technology is the *dual-polarization radar*, which observes both the amount and type of precipitation – being water, sleet, snow or hail. All new radars installed in developed countries are dual polarization radars. As of 2013, 40 out of the 200 radars in Europe have already been updated. The remainder are expected to be replaced by 2025.

Adaptive radar networks, which allow multiple radars to flexibly follow the development of a relevant weather phenomenon, reduce prediction uncertainty in nowcasting. More reliable nowcasting enables decision-makers to make better decisions in situations in which the costs of the incident, but also those of false alarms are significant. (McLaughlin and Chandrasekar, 2009)

The *improvements in the satellite observation systems* in the past two decades have been a crucial driver behind the steady extension of the reliable forecast period. Future improvements in satellite systems can be expected to continue this trend. However, growing uncertainty about funding of these future systems seriously challenges the assumed trend.

The further development of retrieving and analyzing mobile observation data was emphasized by the interviewees. *Mobile observations* include observations from vehicles e.g. data from the windscreen wipers or braking systems, and observations made by individuals with mobile devices. These observations can be automatically collected data in a specified format. A novel approach is to compose informal data points such as pictures or status updates posted in social

[8] Nowcasting concerns very short term weather forecasting 0 – 4 hours ahead at high spatial resolutions (such as road segments) (Browning, 1980)

media (e.g. Hyvärinen and Saltikoff, 2010; Muller et al., 2015). Due to the possible quality problems with this kind of data, it either requires validation or it can be used for validation purposes.

Data fusion means that observational data from different sources, for example measurements from weather stations, road-side rainfall measurements and lightning data is combined and analyzed in conjunction with radar data. Consequently, integrated measurement networks would provide a better picture of the state of the atmosphere. Open data policies, such as the INSPIRE directive by the European Commission (European Parliament and Council of the European Union, 2007) will enable also private weather companies to develop tailored applications based on data fusion.

4.2 Global weather models and forecast skill

The performance indicator representing the capability to predict meteorological conditions is indicated by 'forecast skill'. Nurmi et al. (2013) suggest that atmospheric predictability has improved approximately by 1-day-per-decade during the last 20 years; which was confirmed by ECMWF. Generally, for a given season and area, temperature forecasts tend to perform better than precipitation forecasts. The 1-day-per-decade development is a baseline for the expectation of the development in the future, but it requires some assumptions on technological development and policy measures. The biggest threat to the continuation of this improvement rate stems from research and development budget constraints. The development depends largely on the following three factors:

1. *Computing power*: with faster computers, models can run at higher resolution and phenomena that happen in the atmosphere can be better resolved. The decreasing cost of processing power also enables more sophisticated observation and data transmission instruments and in general lowers the price of all data processing.
2. *Observation infrastructure, especially meteorological satellites:* Running models at a higher resolution requires higher resolution satellite data, which requires maintaining a sufficient satellite fleet and systematic renewal of obsolete satellite instruments. For shorter range forecasts, conventional observations systems are more important, requiring investments in this infrastructure as well.
3. *Computer models, and general meteorological research*: Research is required on the interactions between the atmosphere, land (e.g. vegetation) and ocean and on running the models in an efficient way. Furthermore, the utilisation of the advancements in computing power requires development of more sophisticated models.

In addition to temporal accuracy, also the spatial accuracy of global models has been increasing steadily. ECMWF expects to run their global forecast system in a 10x10 kilometre grid within the next five years and perhaps in a 1x1-kilometer grid in 10-20 years. Current regional very high-resolution models run in a 3x3-kilometer grid. As the spatial accuracy of these models and predictions increases, the role of NHMSs could change, as they are currently the main providers of regional weather forecasts. This could lead to significant rearrangements in the division of responsibilities between different service providers; public and private alike.

4.3 Information and communication technology

As mentioned, ICT has a key role in the development of weather and climate services. Improvements in weather forecast accuracy are partly enabled by advances in computational capabilities. Smoothly working telecommunications are critical for the timely access to weather information; the use of mobile observations increases the reliance on communications even further as the data has to flow in two directions. Combining spatially and temporally accurate weather data with other context-dependent information requires both abundant transmission and processing capacities.

Advances in electronics have enabled the continuing reduction of unit costs in computing and telecommunications. The physical limits of current transistor technologies are acknowledged, but the exponential development is expected to continue in the following decades (Cavin et al., 2012). Thus, the development of computational performance is likely to support improvements in forecast accuracy also in the future. There are, however, other technical challenges that may affect the course of weather service innovation. Firstly, congestion of mobile networks is worsening as both the amount of mobile devices and the popularity of data-intensive services increases. Technological development alleviates the problem to some extent, but the spectrum itself is limited. For example maintaining a reliable road weather service might require specific policy decisions at some point. The second challenge is the growing energy demand of the mobile devices. More advanced network technologies require more advanced signal processing from the device. This, together with the higher capabilities of the devices regarding their computational power, display quality and other features translates into rising power consumption. Although the issue could be addressed with improvements in battery and charging technologies, a more fundamental problem is caused by the waste heat that needs to be dissipated. This problem is however less relevant for road weather systems if the end-user devices are part of the vehicle.

Any advanced road weather system needs to combine and process data of various sensors and sources. Foreseen technological development enables further advancements in such systems, but the aforementioned challenges are likely to guide their design. In light of the challenges, the road weather systems are likely to be centralized (data gathering and processing taking place in a remote service centre) instead of decentralized (data gathering and processing taking place in the vehicle). The configuration of the system will also affect the business models and the diffusion pattern of the services.

5. Innovations in weather services as a means of adaptation in the road transport sector

The use of weather and climate services is closely intertwined with the evolution of a road transport sector's coping range with respect to prevailing weather conditions. Consequently, investment in weather services is beneficial regardless of the realized future state of both climate and society and is, therefore, a robust adaptation measure. The development of weather and climate services can expand the amount of cost avoided, and/or enable improvements in conjunction with product or process development in the road transport sector. This means that adaptation to climate change will be affected by the socio-technical innovations in weather and climate services.

The responses arise either when the weather condition becomes apparent or when the information about the current/future weather conditions reaches the decision-maker. There have already been positive findings suggesting that these measures can decrease the economic sensitivity of the transport sector to weather conditions (Lazo et al., 2011; Nurmi et al., 2013).

This section shows how innovations in weather services can enhance these decisions and increase the benefits of the information for the users. Using the first six filtering steps of the WSCA, we analyse how the investment in weather service capabilities affects the ability to respond to adverse weather conditions. This is done by analysing pre-trip and en-route adjustments. The current level of each step is analysed mainly from the results of the relevant literature, while the innovation prospects and service development were collected from semi-structured interviews (section 3).

Ideally, the (accurate) weather information should be available for the vehicle drivers at the latest on the evening before the trip because they request knowledge about the relevant weather parameters 6-12 hour prior to trip to be able to modify their travel plans (Nurmi et al., 2012; WIST, 2002). On a shorter lead-time, the modifications are more of a reactive nature, such as selection of a different route (Cools and Creemers, 2013). The relevant weather parameters, which climate change is projected to have an effect include at least snowfall, precipitation, temperature, wind gusts and hail (Vajda et al., 2011; Jylhä et al., 2009).

In addition to pre-trip decisions, vehicle drivers can adapt to current weather information by making en-route decisions. Rather than a static decision, an en-route decision is a recurrent or even continuous series of decisions related to driving speeds, effective route choices, stoppages, safety margins and overtakes. Results from earlier studies suggest that on-road driving behaviour is predominantly affected by the prevailing conditions rather than traffic weather forecasts (Kilpeläinen and Summala, 2007; Nurmi et al., 2012; De Palma and Rochat, 1999). However, it seems that up-to-date information during the trip can have a larger impact on the drivers' response. Consequently, the most important meteorological information are nowcasts and observations from road weather stations. The methods for improvement of the efficiency of on-road decision-making should be spatially very accurate, technical by nature and give clear messages of effective/suggested measures (Kilpeläinen and Summala, 2007). These measures could shift the en-route weather information from static weather maps to dynamic decision-making tools such as adaptive route-choice tools.

5.1 Step 1: Accuracy of relevant weather parameters

Based on indirect verification methods (Sihvola and Rämä, 2008), 92% of the days with very poor weather conditions are at the moment forecast already on the previous evening.

Pre-trip decisions

Often, weather parameters relevant for vehicle drivers are combined in a road weather model, which employs as an input a numerical weather forecast and observations from synoptic weather stations, road weather stations and weather radars. The model produces a forecast of road conditions (e.g. friction and visibility), which can be categorized for instance in three classes; 'normal' which implies normal driving conditions and is disseminated as a regular forecast, 'difficult' and 'very difficult' which are disseminated as warnings to the public. Based on an indirect verification of the quality of the extreme winter weather warning system in Finland, warnings are successfully issued on days with a distinctly high accident rate; 19 out of 21 of the days with highest accident rates had been forecast on the evening before (Sihvola and Rämä, 2008), indicating that existing road weather models are fairly accurate in predicting the worst accident days. Direct verification is difficult since no objective measures for poor or very poor road conditions exist.

However, Juga (2012) suggests that a surprise factor due to a missed adverse weather event by a forecast is an important determinant in accident rates, implying that no warning can result in very high accident rates on a given day. Furthermore, Sihvola and Rämä (2008) found that poor or hazardous road weather conditions had been forecast on days when the realised accident rate remained low.

Due to the non-linearity suggested in Juga (2012) and false alarms detected in Sihvola and Rämä (2008), the improvement in the temporal accuracy of road weather models can result in large economic savings, as the forecast at the time point of the requested lead-time (6h-12h) is becoming increasingly accurate as discussed in section 4. As an interviewee pointed out, this increases in importance due to the projected climate change-induced increase in weather variability and potential increase in the surprise effect.

En-route adjustment

The most important feature of meteorological information for en-route decisions is spatial accuracy of road condition nowcasts. Of the NHMSs interviewed, two considered the quality of the observations from road weather stations as 'good'. However, the weather station network often is not of the required density, is only concentrated in densely populated areas or is along the main road network. As mentioned by two NHMS interviewees, this greatly challenged the feasibility to produce spatially accurate forecasts and nowcasts.

To tackle this issue, the technology supplier and the NHMSs suggested two main improvements in observation technology. Firstly, the technology supplier noted that less expensive technology, in the form of *remote road surface state sensors* which enables a denser observation network, has been developed. The installation of these devices is expected to start well before 2020. Secondly, mobile observations have the possibility to create a denser observation network, as for instance vehicles can provide information on road slipperiness from the tires and precipitation volume from the windscreen wipers. NHMSs suggested that this process is likely to happen in the next ten years. However, to maintain quality standards of the localized forecasts, verification of the mobile observations with the nearby (road) weather stations is required. Further development, where cars could communicate weather information to each other without a meteorological service as an intermediate, is in progress. Without verification and quality check by a meteorological service, these services can turn out to be problematic. Furthermore, adaptive radar technology and data fusion introduced in section 4 will enable spatially more accurate nowcasts. The new applications will be available in the next 5-10 years (2020-2025).

5.2 *Step 2: Appropriate data*

Based on the literature review and NHMS interviews, the three-level-index about the road conditions is considered sufficient but not exhaustive information by the vehicle drivers. There is demand for route specific information and combination of road condition data with other relevant data (e.g. road blockages). Current skill rating is still around 90%, since based on interviews and literature (Sihvola and Rämä, 2008) the road weather warnings would already enable informed decisions, if utilised accordingly (see steps 4-5).

Pre-trip decisions

The three-level road weather forecast and warning system is well understood and intuitive to vehicle drivers, according to a user survey conducted by one of the NHMSs. However, according to the survey, vehicle drivers would like to obtain more specific information on the actual timing of the adverse weather, as current road weather warnings usually show similar adverse conditions for the next 24 hours, and more specific information on the actual location of the weather event. This demand was specifically mentioned by two other NHMSs interviewed. However, this demand creates a challenge for the communication as giving detailed temporal information via the traditional dissemination channels (e.g. TV, radio) would require showing multiple weather maps, longer air-time for weather forecasts and harder interpretation of the information. New communication channels, mainly internet and mobile applications are being studied, and new services are expected to emerge in the following years in many countries. This, combined with the improvements in forecast accuracy, enable more time and location specific information.

Route-specific forecasts are already available for road maintenance purposes. These will reach the public in the upcoming years as they are being developed in three of the interviewed NHMSs. In Spain, a pilot project on route-based forecasts for three test-case highways has been implemented through an EU FP7 funded project called FOTsis (www.fotsis.com/).

In addition to weather conditions, more informed pre-trip travel decisions should take into account other relevant information, such as road blockages (e.g. construction work, summer festivals etc.) or expected amount of traffic, pointed one of the NHMSs. An example of such data combination is offered by the Bavarian traffic information agency (Bayerninfo-see http://www.bayerninfo.de/planner) which, next to weather information, offers information on real-time events, traffic conditions, travel times and multi-modal services (Scheider et al., 2010).

In Finland, new services that combine data from different sources, and new online and mobile applications that would enable the technical execution, have been planned. In the UK, Met Office has a system which is designed to forecast weather for different routes for road maintenance purposes. It is based on the road weather model of the UKMET, but has a much higher spatial resolution and accounts also for non-weather factors. These services are not available to the public yet, but are expected to be opened for wider use before 2020 and will likely to be integrated to other route-planning tools in the future (2020-2030).

En-route adjustment

Since drivers tend to underestimate the severity of driving conditions compared to what expert reviews or road weather station information would suggest, bringing up-to-date information of the current road conditions to the vehicle drivers is important. Especially the slipperiness of the road surface is a challenging parameter for the vehicle drivers to estimate through their own perception. (Kilpeläinen and Summala, 2007).

A combination of appropriate road condition, weather data and relevant data from other sources, and effective real-time communication to the vehicle drivers is at the heart of Intelligent Transport Systems (ITS). For instance, one of the interviewed NHMS mentioned that layer-based technology will allow users to select the relevant weather and other parameters to be shown on the screen of a navigation system. An EU FP7 funded project ROADIDEA which studied innovations in transportation, listed this as the main development target in the near future. Furthermore, inaccessibility of data and the location of data collection and calculation were listed as the main barriers for development. (Roine, 2010) ITS was mentioned as an important field of research in the interviews. The development is a high priority for NHMSs (2015-2020), but also for many private weather companies.

The driving and management control in road transport is increasingly integrated into technical systems which adjust to different driver needs. The vehicle infrastructure integration enables either vehicle-to-vehicle or vehicle-to-infrastructure communications and has the potential to improve the information provided to drivers (Petty and Mahoney, 2007). A leading global example is a real-time in-vehicle traffic information system called *Smartway* in Japan which reaches over 34 million drivers. Japan invests over 500 million euro annually into ITS (Ezell, 2010). In the European Union, smart transport solutions are applied; however, in a fragmented manner, in mono-modal instances, in geographically isolated domains, and incompletely (European Union, 2011).

Implementation of ITS requires intensive cooperation between public authorities, regulators, the automotive industry, road infrastructure management, NHMSs and/or private weather information companies, cloud service providers and other agents in the evolving field. This change does not take place instantly and without significant investments in Europe (2020-2040). Meanwhile, the development of “traditional” sources of information such as radio, satellite navigation devices (-2020) and mobile applications (-2020) will be important.

5.3 *Step 3: Access to weather information*

Currently, approximately 60% of the drivers have actively or passively received weather information prior to their trip (Cools and Creemers, 2013; Sihvola and Rämä, 2008).

Pre-trip decisions

Traffic weather information systems should be easily accessible to drivers and used by a considerable proportion of them to have an effect on traffic safety and pre-trip decisions. In principle, information is accessible to everyone constantly through various channels: radio, television, internet and mobile applications for different platforms. However, according to road side surveys, user rates for road weather information remain somewhat low (Kilpeläinen and Summala, 2007; Sihvola and Rämä, 2008). In a road side interview by Sihvola and Rämä (2008), 62% of the drivers had actively looked or passively received weather information prior to the trip. In Belgium, a study found that 60% of the respondents acquired weather information on a daily basis; television being the most important medium. However, the choice of media did not play a significant role in the travel behaviour. (Cools and Creemers, 2013). Furthermore, Kilpeläinen and Summala (2007) find that especially young adults are hard to reach via traditional channels. Therefore, we conclude that currently at least 40 % of the vehicle drivers are not familiar with the road conditions prior to a trip.

Push-based mobile applications were identified by interviewees as one innovation to better reach the public. The applications would use the location of the mobile device and send messages to mobile phones either via pre-installed, which would require cooperation with telecom operators, or downloaded "apps", which would require an active decision from the user to install the app and allow it to send push-messages. However, a steady increase in the use of mobile weather applications has been witnessed in Finland (Harjanne and Ervasti, 2014), and based on a survey undertaken in Canada (Silver, 2014), along with telephone calls, text messages and "Cell-phone pop-ups" were seen as the most preferred media to disseminate weather warnings. Therefore, the potential of the push-based messages can be regarded as substantial. Indeed, several new applications are being developed particularly bearing the hard-to-reach young adults in mind. These services will most likely be available in the near future (2015-2020).

En-route adjustments

En-route weather information is still usually based on traditional car radio system. However, two of the NHMSs interviewed are developing nowcast-based weather warnings that will be communicated to satellite navigation devices. This service is already available in one of the interviewed countries, but only for specific navigation devices. In the other two NHMSs these services were considered to be something that commercial companies should provide.

Services for mobile devices are also being developed. However, the safety aspects of using mobile devices need to be considered; for instance Drews et al. (2009) found that dialling or reading text messages from mobile devices is riskier than speaking on the phone or even driving intoxicated. Thus, mobile services should be developed so that the driver does not need to actively search or even read information. Push-based applications with voice alarms, which would warn automatically if the driver is approaching adverse weather conditions or other disturbances in traffic, are being developed. (2015-2025).

5.4 *Step 4: Comprehension of the information*

Approximately 85% of the drivers that had acquired road weather information considered it easy to use and interpret. Studies also show that road weather information has the ability to improve drivers' perception of the actual road conditions. (Sihvola & Rämä 2008; Kilpeläinen & Summala, 2007).

Pre-trip decisions

Sihvola and Rämä (2008) suggest that those who had acquired weather information considered it easy to interpret and use. The stakeholder interviews confirmed this fact, revealing that comprehension of the three-level forecast and warning system is not a problem for users.

En-route adjustments

Studies show that the drivers who receive weather information before the trip have a more realistic perception of the road conditions than other drivers. (Kilpeläinen and Summala, 2007; Sihvola and Rämä 2008).

In general, drivers tend to rate the driving conditions to be better than the forecasts or actual observations indicate. Therefore, en-route information can improve drivers' judgement about the current conditions, especially if it is considered more reliable than driver's own perception of the weather (Kilpeläinen and Summala, 2007).

5.5 Step 5: Ability to respond timely and effectively

Sihvola and Rämä (2008) and Kilpeläinen and Summala (2007) show that about one third of those who had acquired weather information prior the trip, had actually changed their travel plans. These studies did not reach those drivers that had already cancelled their trips. Cools et al (2013) finds that 45-60%of vehicle drivers did not respond to weather information; the precise percentage depending on the purpose of the trip. Therefore, a conservative approximation of this step falling between 33% and the average of 45-60% is 40%.

Pre-trip adjustments

In Sihvola and Rämä (2008), one fifth of the drivers had made or had considered making changes to their travel plans based on weather forecasts. In Kilpeläinen and Summala (2007), only 6 % (or one third of those who had acquired weather information) of the drivers reported any changes in travel plans before or during the trip. This study, however, did not reach those who had already cancelled or postponed their trips. Both studies found that approximately one third of those who had acquired weather information prior to the trip had changed their travel plans, and neither of them included those who had cancelled. The most common change was reserving more time for the trip. (Sihvola and Rämä, 2008; Kilpeläinen and Summala, 2007)

Cools et al. (2013) studied the response of vehicle drivers to weather information via questionnaires in Belgium. They found that the response is heavily dependent on the purpose of the trip and the forecasted weather phenomenon. Of the shopping and leisure related trips, a far greater share of the respondents were ready to cancel the trip in case of forecast of bad weather (over 30%) than of the work or school related trips (under 10%). The study showed that people react with high variation to different forecast weather phenomena, in particular more strongly to those weather phenomena that they are not used to.

Based on the interviews, NHMSs acknowledge the problem of low response rates. Response rates can be improved with clearer messages and cooperation with other institutions, such as the police. For example, if extremely poor weather conditions are forecast several days ahead, the warnings can be issued on television channels (although in some countries this is not possible) and other media partners can be informed. The police can advise people to leave their own cars home or work from home, if possible. One of the interviewed NHMSs stated that they have already seen success in the cooperation with the authorities, as the amount of traffic has been significantly reduced during those days that warnings have been distributed actively with authorities mainly in national news. An example of a social innovation is the possibility of replacing work trips by collaborative technologies and working from home when needed. According to a study about New York in 2030, 30% of the commuters would have the possibility to stay home in the case of poor weather. The possibility for telecommuting is likely to improve the ability to respond with trip cancellations (Ukkusuri and Ramadurai, 2009).

En-route adjustments

Driver responses to weather information acquired before the trip are non-existent based on Kilpeläinen and Summala (2007) or of too low magnitude based upon De Palma and Rochat (1999), Sihvola and Rämä (2008) and Rämä and Kulmala (2000). However, up-to-date information on the road can have a larger impact on the driving behaviour (Kilpeläinen & Summala, 2007).

Consequently, examples of measures to improve the response of drivers include standardized variable message systems that display concrete driving behaviour instructions (Kilpeläinen and Summala, 2007), such as maximum allowable speed or painted signs on the road surface that are only visible in specific conditions (implemented in the Netherlands, (Clark, 2012)). Other measures could include push-based instruction from mobile or satellite navigation devices or integrated decision-making systems on vehicles. The latter type of options are expected to be implemented in a somewhat more distant in the future (2020-2040). Based on the interviews and Kilpeläinen and Summala (2007), spatially and temporally accurate warnings could improve the response of vehicle drivers as they would find the information more reliable than the earlier forecasts.

5.6 *Step 6: Actual effectiveness of the responses*

Responses, such as cancellations (Maze et al., 2006) or even small speed reductions (Nilsson, 1982), are efficient ways to reduce accidents. Nurmi et al. (2012) estimate this step to be 80%, as responses, should they happen, are effective.

Pre-trip decisions

The effectiveness of responses is mixed (Stahel et al., 2014). Cancellation and postponing of trips are obviously effective ways to mitigate the effects of poor road conditions (Maze et al., 2006). Cancellations of trips are more common for leisure-related trips than work-related trips (Cools and Creemers, 2013; Chung et al., 2005). This suggests that leisure trips are much more sensitive to weather information and weather conditions than work trips. For example, in Kilpeläinen and Summala (2007), leisure trips were clearly underrepresented in the road side interviews during very poor driving conditions, suggesting that most of the trips had been cancelled or postponed. Other possible responses are mode changes and route changes. However, these are less frequently used than postponing (Khattak and De Palma, 1997; De Palma and Rochat, 1999). Admittedly, cancellation and significant postponement of a trip will entail disutility for drivers. Supposedly, a significant part of these costs are not monetized. Conversely, there may be also savings such as unconsumed fuel. These costs and benefits of rescheduling are not taken into account in section 5. The same applies for the secondary cost effects of responses discussed below.

However, other responses next to cancellations are not as successful: even though respondents stated that they had acquired information and sometimes even reserved more time for the trip, the prior acquisition of weather forecast information had no effect on on-road-behaviour, which can be better influenced by real time information (Kilpeläinen & Summala, 2007). In other studies the prior acquisition of weather information has influenced the driving behaviour during the trip by small speed reductions (Khattak and De Palma, 1997; Sihvola & Rämä 2008).

En-route adjustments

Even small changes in average speeds have a significant, non-linear reduction in the accident rates. Variable message signs controlled on the basis of automatic classification of road condition situation were found to reduce the winter-time accident risk by 13% and summer-time by 2% (Rämä and Kulmala, 2000). Nilsson (1982) found that a 1 km/hour reduction in average speed reduced the amount of accidents in motorways by approximately 3-4% and on roads with 50 km/hour speed limits the reduction was 4-6%. Drivers are also found to comply with variable speed limits better than to conventional ones (Scheider et al., 2010). The integration of road weather information, mobile devises, cars and road infrastructure will enable coordinated responses in the future, some decades forward (2020-2040).

5.7 *Summary of the innovation prospects*

Table 1 summarizes the innovation prospects and combines the relevant expected improvements with the estimate of the uptake schedule. The estimates of the timing of the uptake and the current level of each step are based on the preceding analysis. The improvements are again categorized based on which step of the WSCA they are expected to bring improvements.

Table 1. Summary of the innovation prospects between 2015-2020 and 2020-2030

WSCA steps 1-6	-2020	2020-2030
1. Accuracy	Development of road weather models; denser road weather station network; data fusion and more accurate knowledge of relevant parameters for now casting purposes. Current: 92%	Adverse weather can be forecast 1 day earlier with the current accuracy; surprise events very rare; observations from cars to weather forecasts system, data fusion and adaptive radar networks will improve. Spatial accuracy of current observations and now casts
2. Appropriate data	Development of route-based forecasting; Weather information combined with other relevant information; development of layer-based technology (user selection of relevant weather parameters on one map) Current: 90%	Route-based forecasting available; Relevant information processed and selected automatically for the vehicle drivers
3. Access	Improved internet platforms; mobile applications; push-based applications; satellite navigation systems; Current: 0.62	Infrastructure, including weather services, communicates directly with the information system of the vehicle, ITS;
4. Comprehension	Improved en-route information will enable better judgement on the current conditions; Current: 0.85	Changes in weather parameters automatically analysed by the information systems of the vehicles.
5. Ability to respond	Variable message systems and road signs, concrete and spatially accurate advice from mobile devices and satellite navigation systems. Current: 0.4.	Telecommuting possible for a larger share of commuters.
6. Effectiveness of response	Current: 0.8	Coordinated responses

Figure 1 shows the current level of each step, also given in Table 1. It also shows the estimated increases in the current levels for each step (baseline in Table 2). A tentative system response analysis for the future values is performed in Section 6.

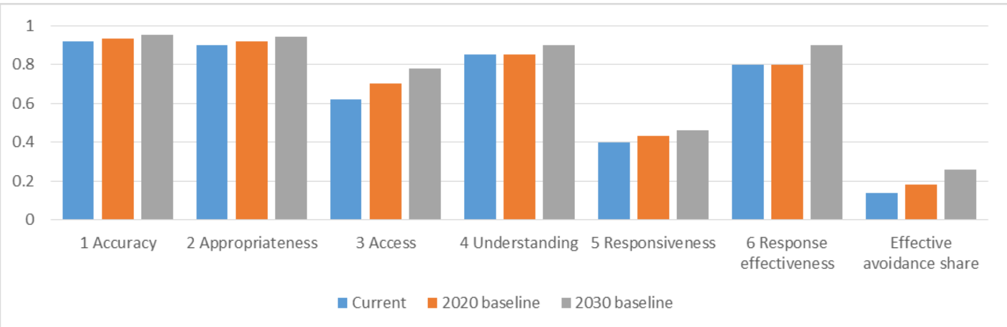

Figure 1. The current level of each WSCA step and the estimated increase in each step

6. Discussion

Road transport is facing two types of trends that are affecting the level of accidents in the opposite directions. The expected increase in the extreme weather related costs is interlinked with expected decrease of accidents costs due to technological and societal development (Nokkala et al. 2012). There are some estimates of the expected accidents costs taking both of these trends into account (Andersson, 2010; Nokkala et al., 2012) but due to high level of uncertainty of the future state of the sector, it is questionable to use these estimates for economic analysis. Nurmi et al. (2012) estimate that the annual accidents costs due to extreme weather in Europe are currently close to 24.4 billion euros. Consequently, this estimate of current accident costs is used in the sensitivity analysis for the magnitude of the annual savings of the weather service improvements. Nurmi (2012) estimate that only approximately 14% of the hypothetical maximum benefits of weather services (in terms of accident prevention) are currently realized at the end of the weather service chain in road transport. The estimate is based on the decay of value through the entire chain, expressed as product sum as explained in section 2.2. The constituting elements of the product sum, and the eventually resulting fraction realized are shown in Table 2 in the "Current" column. The exact formula of the effective avoidance share was introduced in section 2.

Table 2 presents a tentative system response analysis of how the improvements in the weather service chain would result into economic benefits. This can be viewed as the authors' best guess based on the innovation prospects and earlier experiences summarized in Table 1. The improvements in steps 2-6 in Table 2 are potential development pathways for weather services for road transport. We have developed two futures scenarios - baseline and high investment. The scenarios are developed based on the analysis presented in section 5. In the high investment scenario, progress in each step is defined to be twice as fast as in the baseline scenario. The improvement in step 2 is assumed to be modest due to the high initial value; however, based on the interviews, NSHMSs are putting effort on further improving this step. A larger improvement is assumed in Step 3 where innovations play a crucial role and several new ways to deliver information are being developed. In steps 4 and 6, no improvement is assumed in the baseline scenario until 2020, as this is heavily dependent on the end users and their behaviour. However, with further improvement in technologies, understanding and the effectiveness of the response will improve as more control is given to vehicles. The baseline of Step 5 is expected to improve earlier when more information is provided to the navigation systems.

In the base case, until 2020, 18% of the hypothetical maximum benefits are reached, and until 2030, 26% of the hypothetical maximum benefits are reached. In the high case, until 2020 26% of the hypothetical maximum benefits are reached and until 2030 40%. It is worth noting that this analysis is only done to illustrate how investments in weather services and respective innovations would translate into economic benefits as reduced accident costs. Other savings, such as time savings, should be added to the calculations; however based on earlier studies (Nokkala et al., 2012; Leviäkangas et al., 2007) those are likely to be small in value related to the accident costs. The system response analysis allows decision-makers to compare alternative investment strategies and/or conduct cost-benefit analysis of investment in projects altering the weather service chain. Consequently, the analysis is not meant to give accurate predictions of the future benefits, and the economic benefits should be interpreted as giving the expected magnitude of the future benefits given the chosen investment strategy. Also by manipulating different steps, benefits of investment in particular area of the weather service chain can be approximated.

The annual monetary benefits in the form of reduced accident costs are depicted in the last row. The disparity between base and high scenarios is around 2 billion euros annually by 2020 and already over 3 billion euros annually in 2030.

Table 2. Tentative system response analysis and resulting economic benefits

WSCA steps	Current	2020 baseline	2020 high investment	2030 baseline	2030 High investment
1 Accuracy	0.920	0.935	0.95	0.95	0.98
2 Appropriateness	0.900	0.920	0.94	0.94	0.98
3 Access	0.620	0.700	0.78	0.78	0.94
4 Understanding	0.850	0.850	0.9	0.9	0.95
5 Responsiveness	0.400	0.430	0.46	0.46	0.5
6 Response effectiveness	0.800	0.800	0.900	0.9	0.95
Effective avoidance share	0.140	0.18	0.26	0.26	0.40
Road accident max. damage potential (10^9 €)*	24.4	24.4	24.4	24.4	24.4
Prevented damage costs/year (10^9 €)	3.4	4.4	6.3	6.3	9.8

*current accident costs + estimate of the avoided costs

Table 2 shows that currently the largest gaps in the benefit realisation are related to WSCA steps 3 (access to up-to-date information) and 5 (ability to respond). A large share of the drivers does not acquire weather information prior to their trips and during the trip base their opinions about the weather conditions mainly to their own observations. Therefore, the development in the communication technology is a key driver in this step. New ways to reach the vehicle drivers, such as new applications on mobile devices, services for satellite navigation devices and variable message systems are being developed. On the other hand, based on past studies, it seems that the responses to weather warnings are of too low magnitude both prior and during the trip.

So what are the key investment decisions that affect the realized future scenario and the economic benefits? Policy instruments and economic constraints affect the speed, magnitude and the direction of the innovation. This impact of economic activity and policy on development and diffusion of new technologies can be labelled as *induced innovation* (Nordhaus, 2002). The innovations in road weather services are likely to rely on policy decision in two key ways. First, the development in weather services is highly dependent on enabling core technologies, especially ICT and space technology. The advancements in these technologies are often results of publicly funded basic or applied research or research infrastructure. Thus, public investments are necessary to support the research and development work on which the future road weather services is built on. Second, many of the components in the current and envisioned road weather services are directly reliant on public funding or regulation. The weather observation infrastructure as well as the road infrastructure in general is likely to remain publicly funded. Advanced systems require working high-bandwidth communications across large areas that contain both densely populated urban areas and scarcely populated rural locations. Ensuring reliable communication in these conditions likely requires prioritization on policy level in situations in which the data traffic is congested and subvention in areas where the market is small or undeveloped. Yet, although the development is highly policy dependent, the private sector has a major role in producing and diffusing technical and practical innovations. Preferred policy is then such that it involves industry in developing new services and aims to create incentives for companies to create novel solutions for road weather services.

7. Conclusions

Based on both literature review and the user survey, the expected changes in weather variation and in the extreme weather patterns seem the main threats that climate change poses to transport sector in Europe. However, keeping in mind both the high level of uncertainty in climate predictions and the fact that users of transport modes mainly react to adverse weather at the operational level or at the tactical level, costly alterations in transport infrastructure is not likely to be the most efficient adaptation strategy. Consequently, an important part of CCA in transport sector goes through processes that enable better operational and tactical level decision-making in adverse weather situations. Innovation in weather services is a crucial building block in this process.

The aim of this paper was to assess the role of innovations in weather service provision to reduce the negative impacts of climate change-induced increase in the frequency and severity of extreme weather events in the road transport sector from the perspective of the vehicle driver.

It is clear that the potential value of weather service provision has not been fully realised. Investments in research and development, leading to innovations, were shown to be beneficial in terms of increase in the avoided accident cost. These innovations are examples of the improvements in the weather service chain which will significantly decrease the vulnerability of road transport to extreme weather event and the weather related costs, thus being an important part of the sector's climate change adaptation process. Innovations enhance automatic adaptation capabilities which thereby extend the coping range of the road transport system. In turn this allows us to better exploit learning options and thereby invest later on more effectively in adaptation measures. The benefits of the innovations are naturally dependent on the overall development of society and the climate.

The first limitation of the analysis presented in this paper is the knowledge gap of the impacts of climate change on the transport sector, and consequently the lack of estimates related to the accident rates and costs in future climate and society. Paradoxically, it stems from the same reasons as the suggested need for the robust, no-regret adaptation options.

Another limitation of the analysis is related to the qualitative nature of the WSCA and resulting need to estimate the quantitative level of each step based occasionally only on qualitative data. However, WSCA is a comprehensive tool as it enables to assess the full weather service provision chain from the generation of the information all the way to the end used response and resulting benefits. The development of the WSCA is leading toward quantitative indicators with objective criteria to assess the current status and the development need of each step. This would enable the use of the approach in multiple contexts and more objective estimates of the benefits and development needs. The benefit estimates could be used in cost benefit assessments of selected investments.

Acknowledgements

This study has been conducted as part of the EU FP7 TopDAd project, grant agreement 308620, which aims to model the impacts of climate change and identify adaptation options for the energy, tourism and transport sectors through an ensemble of climate, sector economic and macro-economic models. We thank the three anonymous peer-reviewers for their valuable comments, which substantially improved the quality of the paper, and David Lazarevic for his comments on the manuscript.

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Cambridge University Press

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Journal of Benefit-Cost Analysis, 7, 488-522.

https://doi.org/10.1017/bca.2016.18

IV

J. Benefit Cost Anal. 2016, 1–35
doi:10.1017/bca.2016.18

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Green Roof Cost-Benefit Analysis: Special Emphasis on Scenic Benefits

Abstract: This article presents a green roof cost-benefit analysis (CBA). Green roofs are roofs which are partially or completely covered by vegetation. We discuss the benefits and costs of light self-sustaining vegetated roofs. The benefits of the ecosystem services (ES) provided by green roofs can be classified into private and public benefits. We apply the selected valuation methods first in Helsinki, Finland and subsequently explain how results can be transferred to other urban locations. Past research and this study show that private benefits are usually not high enough to justify the expensive investment for a private decision maker. However, when the public benefits are added to the private benefits, social benefits are higher than the costs of green roofs in most cases.

Past research quantified most types of the benefits, excluding scenic and biodiversity benefits. Scenic benefits denote the intangible benefits that people derive from the presence of green space, including at least aesthetic and psychological ones. In this article, special emphasis is placed on the valuation of the scenic benefits; these are among the most challenging benefits to valuate in monetary terms. We employ hedonic pricing theory, implemented via spatial regression models, and green roof implementation scenarios in order to estimate the aggregate willingness to pay for a "unit" of green roof. The results show that the scenic benefits can be a significant attribute in cost-benefit calculations. Yet, the amount of benefits strongly depends on the green roof design.

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Keywords: aesthetic value; green roofs; scenic benefits; urban ecosystem services; urban planning.

1 Introduction

Green roofs are roofs that are partially or (almost) completely covered by vegetation as a result of planned action rather than neglect. Green roofs are an increasing feature of cities' urban planning tool set. Local adaptation plans around the world list green roofs as a tool for both storm-water management and attenuation of the urban heat-island effect, as is the case for adaptation plans of Vancouver, Copenhagen, London, Melbourne, Singapore, Chicago and Barcelona (see Copenhagen, 2015, for a review and links). Green roofs also decrease the energy consumption in buildings (e.g., Berardi et al., 2014) and are identified as a valuable strategy to make buildings more sustainable, and increase urban green in cities while avoiding the negative effects of lowering densities. The inclusion of green roofs to the urban planning tool set creates a high demand for cost-benefit studies to support decision-making with regards to choosing the right implementation strategy, for example, choice of plant cover, needed incentives and efficient scale (U.S. Government, 2011). This article aims to contribute to this increasing demand, and convert the green roof benefits into monetary terms, aggregate monetary values over time and compare benefits to the costs of green roof installation. We focus on the benefits and costs of thin, lightweight, left-sustaining green roofs with minimal maintenance requirements – often labeled as extensive green roofs in the literature (e.g., Berardi et al., 2014).

The benefits and costs of green roofs have been studied for several sites, including New York (Rosenzweig, Gaffin & Parshall, 2006; Bianchini & Hewage, 2012), Toronto (Bantinget al., 2005), Atlanta, Georgia (Carter & Keeler, 2008; Whatley, 2011), Michigan (Clark, Adriaens & Talbot, 2008) and Seoul, South Korea (Shin & Kim, 2015). Additionally, the costs and benefits of green roofs have been studies in more general settings than a specific city context in Germany and Brazil by Porsche and Köhler (2003), in Belgium by Claus and Rousseau (2012), and in the USA by Porsche and Köhler (2003) and Sproul, Wan, Mandel and Rosenfeld (2013). All studies quantified benefits pertaining to membrane longevity, building energy savings, storm-water management and air-quality benefits, while many also quantified reduction of the heat-island effects, noise insulation and greenhouse gas reduction. Scenic benefits that include at least aesthetic and psychological benefits, and biodiversity benefits are usually left out of the analysis. The exceptions are a study by Rosenzweig et al. (2006) in which aesthetic benefits were included by assuming a certain willingness to pay (WTP) for New York residents, and a study by

Bianchini and Hewage (2012) in which percentual (2%–5%) increases in the value of the nearby properties were assumed. Taking into account the state of the art, our main contributions to the literature are (1) ease the transferability of the value estimates by providing detailed information on the valuation methods and the roles of different assumptions and parameter values in the estimates of benefit and cost items and (2) inclusion of scenic value benefit item into the analysis based on a formal and trackable analysis rather than a guess.

The paper is structured as follows: We first discuss the valuation of benefits that people obtain from the consumption of ES, and explain the choice of discount rate. Next, we present all the building blocks and benefit items of a CBA of green roofs and the options to assess them. The presentation is based on an application in Helsinki, Finland, but with added information on how the same item can be treated for another location. In this way we intent to contribute to the spread of benefit-transfer approaches so as to make CBA of green roofs affordable. One section has been dedicated to the valuation of scenic benefits since previous measures of the scenic value individuals place on green roofs are weak at best. Subsequently, we review the costs of green roofs, and finally we discuss the net present value (NPV) of green roofs and present a green roof implementation scenario in which 10% of the city's roof area is being greened, while a distinction is made between public and private costs and benefits. In the conclusion, we summarize the results and reflect on policy options such as needed incentives, and discuss the limitations of our approach.

2 Economic Background

Ecosystem services (ES) are benefits that people obtain from ecosystems (Millennium Ecosystem Assessment, 2005). The concept of ES is useful as it allows to separate different types of services provided by an ecosystem, in this case a collection of green roofs. This allows the valuation of each ecosystem service separately. Within urban areas, the primary issue from the perspective of human well-being is whether urban settlements are able to provide a healthy and satisfying living environment for residents. The emergence and growth of cities is (usually) based on the proximity of producers and consumers that creates common advantages in productions and consumptions. As a consequence, the productivity per acre in cities can get so high that it pushes up land and real estate prices (Brown, 1974). This creates pressure for ecosystems in terms of high opportunity costs of urban green space, while the benefits of ES are not often explicitly valued. The trade-off between ES and urban economic activity is not evenly weighted in the absence of such assessments. Consequently, the interest in ES is rising also for urban environments, which ties in with the need of revising the concept of sustainable urban planning. This article focuses on valuation of benefits of ES of an ecosystem that is not yet a standard solution in most cities: green roofs. The addition of green roofs to the green infrastructure portfolio is promising, as green roofs can raise the supply of ES while avoiding the negative effects of lowering densities.

2.1 Defining the economic value of ecosystem services

Based on the preferences of an individual, the "equivalent in money" can be calculated for a change in the quantity or quality of ES, where the sum of money represents the equivalent effect on the welfare of an individual (Freeman, Herriges & King, 2014). The valuation of urban planning realization effects, for example, trough changes in real estate value, is eventually based on the theoretical concepts of compensating variation and equivalent variation, first adapted to commodity (rather than the price) space by Mäler (1974):

$$v(\mathbf{p}, q_1, y - CV) = v(\mathbf{p}, q_0, y) \tag{1}$$

$$v(\mathbf{p}, q_1, y) = v(\mathbf{p}, q_0, y + EV). \tag{2}$$

The compensating variation, CV in equation (1), is the maximum amount of money that an individual would be willing to pay (WTP), so as to achieve the higher supply of ecosystem service q_1 as compared to $q_{0.}$ The equivalent variation, EV in equation (2), is the minimum compensation that an individual would accept (WTA) to forgo the raise of supply of ES from q_0 to q_1 associated with the enhancement of an ecosystem. The difference between the concepts is that the monetary "value" is measured at different points, either at q_1 or at q_0 in the ES quantity/quality dimension. In the case of green roofs, the correct welfare measure is CV – based on the property rights argument, as the beneficiaries of green roofs do not yet possess the higher level of ES. (The property rights argument is explained, for example, in Boadway, 2006; Arrow et al., 1993).

Hanemann (1991) showed that in the case the good q has a perfect substitute x_i that can be bought at the market place for a price p_i, and assuming interior solution so that $x_i > 0$, both at q_0 and at q_1, there are no income effects and the CV can be calculated by $(q_1 - q_0) * p_i$. Consequently, if the ES replaces a market good/service that would have been bought by the decision maker regardless, it is straightforward to use this avoided costs as a value measure. It should be noted that we do not claim that green roofs are a perfect substitute for conventional roofs but that some ES it provides are perfect substitutes for some market goods. In the subsequent chapters, we use this as a basis for our valuation methods and show that many of the benefits of green roofs are in the form of avoided costs, for example, energy costs or stormwater-related costs.

2.2 Applied valuation methods

There is a variety of methods developed for estimating the value of ES, discussed in detail in several articles (e.g., de Groot, Wilson & Boumans, 2002; Kaval, 2010). Valuation methods all share a target for attributing a monetized value to the benefits obtained from a change in quality or quantity of ES. We discuss only those we have applied in the green roof valuation. The choice of method is dependent on the function of the ecosystem service.

Green roofs are a technical solution that takes advantage of the regulating properties of the vegetation and substrate layers. Many of the ES they provide can be classified into regulating services. These services benefit people mainly by enabling avoidance of other costs. The natural choice of the valuation method is then "Avoided costs" as suggested by de Groot et al. (2002) or on more theoretical terms by Hanemann (1991).

Green roofs, however, benefit people also in subtler ways. There is evidence that green roofs can provide urban habitat for wild species and help to increase the local biological diversity (Coffman & Waite, 2011; Madre, Vergnes, Machon & Clergeau, 2014; Gabrych, Kotze & Lehvävirta, 2016). This "refugium" function of green roofs could be tackled with contingent valuation methods to some extent, but is left out of the scope of this study as it would suffer from lack of adequate quantitative input. Yet, green roofs can also provide aesthetic and psychological benefits for people in urban areas. These benefits have been grouped together in this article as "scenic benefits" for methodological reasons. Hartig, Mang and Evans (1991) proved that experiencing naturel has restorative outcomes and the effect can last for several weeks after the experience. It is widely known that property prices are positively affected by the view and closeness of green space. In Finland Tyrväinen and Miettineni (2000) have shown the positive relationship between the urban green and property prices. We confirm this relationship in our analysis. Hauru, Lehvävirta, Korpela and Kotze (2012) showed that changing the visual setting from urban built-up area to an urban forest offers restorative benefits, while Lee et al. (2015) show that restorative benefits are even elicited by a small urban green roof and are comparable to that of a small urban park. We use the results from the hedonic regression analysis to indicate an upper limit for the scenic value of urban parks, expressed as mark-up of the square meter price of involved real estate.

The scenic value can also be studied by means of the contingent valuation (CV) methodology. Our choice in favor of hedonic pricing (HP) is explained by: (1) HP is the appropriate methodology for valuation of services and disservices that are intrinsically dependent on the *location* of households (Brander & Koetse, 2011); (2) we are able to avoid the bias of stated preferences contained in CV (Brander & Koetse, 2011); (3) there are only a couple of green roofs installed in Helsinki and people lack experience to the extent of turning stated preferences into mere guesses (Murphy, Allen, Stevens & Weatherhead, 2005); and (4) we would expect the results to be of the same magnitude in the case of a CV study (Blomquist, 1988; Carson, Flores, Martin & Wright, 1996; Shabman & Stephenson, 1996; Bateman, Lovett & Brainardi, 2004; Ghermandi, van den Bergh, Brander, de Groot & Nunes, 2010). Expected differences and uncertainties in the hedonic estimates and the use of the proxy are handled by using lower and upper bounds for the value.

2.3 Choice of discount rate

Weitzman (2001) concluded – based on a survey of more than 2000 economists – that the appropriate discount rates for environmental BCA can be summarized in the following simplified scheme based on the project's lifetime: 4% for the immediate future (years 1–5), 3% for years 6–25, 2% for years 26–75 and 1% for years 76–300 and 0% for the benefits and costs for years after 300. The declining trend in the discount rates can be backed by the economic theory on uncertainty (see Gollier & Weitzman, 2010). However, for simplicity and to ease the interpretation of the results, we have applied a single interest rate of 3% which approximates the discount rate schedule above. This choice is also in line with the fixed long-term interest rates applied to mortgages and long-term investment loans. The same interest rate of 3% is also recommend by the U.S: Office of Management and Budget (2003) and by the German treasury. Slightly higher social interest rates are recommended by France (4%) and UK (3.5%) (EU, 2008).

3 The benefits of green roofs in Helsinki and the transferability of the results

In this section, we show how each benefit item of green roof CBA can be treated. We measure the benefits in Helsinki, the capital of Finland, with around 625 000 inhabitants, and a metropolitan area of around 1.1 million inhabitants. We compare our findings to results from the literature. We also divide the benefits between those that directly accrue to the property owner/resident and those that are shared by the wider public, such as savings on in public spending and health benefits. For each benefit, we also show how the results obtained from Helsinki change when changing the city-specific environmental or infrastructural parameters. Furthermore, the valuation methods described in this section can be applied to any other urban location. To ensure replicability and transferability, we take some space to describe the methods.

3.1 Membrane longevity

The historic experience built up with green roofs points at approximately doubling the lifespan of the roofing membrane. This amounts to an additional 20 years lifetime compared to a conventional roof. We use this assumption so that the life cycles are 20 and 40 years for conventional roofs and green roof respectively (Porsche & Köhler, 2003; Liu & Baskaran, 2003; TRC 2007). This is fairly conservative as 40 years is the minimum life cycle of a green roof in other cost-benefit analyses, for example, Bianchini and Hewage (2012). The price of installing a regular bitumen roof in Finland is around 43€$/\mathrm{m}^2$, which includes the value-added tax, as this is a private cost (taxes are removed when analyzing the social benefit and costs). Hence, the NPV of the benefit is 23.8€$/\mathrm{m}^2$ or the discounted price of the reference roof. The factor that determines this benefit is the local cost of the chosen reference roof that the green roof is compared to.

3.2 Energy cost savings

Green roofs have an effect on the heat transfer properties of the roof via three different phenomena (Berardi et al., 2014): (1) substrate increases thermal capacity and decreases thermal transmittance through the roofs, (2) foliage shades, under the foliage convection provokes heat thermal exchange but foliage absorbs part of the thermal energy for photosynthesis and (3) substrate and vegetative layers induce evaporative and evapotranspiration cooling. These phenomena have the potential to reduce the energy consumption for heating in the winter and for cooling in the summer. The benefits of these processes are determined by the type of vegetation, substrate depth, availability of water, local climate and building type (Liu & Baskaran, 2003). We employ the avoided cost method to estimate the savings in the energy costs for an extensive green roof in Helsinki. Our results below show that when moving toward warmer climates, the energy savings in total tend to increase as the cooling energy benefit increases considerably faster than the heating energy benefit decreases.

3.2.1 Energy cost savings for heating

We explore the impact of a green roof on the heating consumption of a building by comparing the heat loss of different types of roof. Green roofs reduce the thermal transmittance of a roof, thereby improving the insulation capacity. This effect is highly dependent on the building envelope characteristics on which the green roofs are placed. Generally, in non-insulated buildings, the impact of green roofs is much higher than in insulated ones, whereas the better the insulation of the roof, the lower the contribution of green roofs. In cold, heating dominated climates, the insulation properties of the roof carry the highest significance as the heating load benefits from a low U value (U is the coefficient of thermal transmittance). (Roche & Berardi, 2014). More complex models have been developed, most notably by Sailor and Hagos (2011) but the use of these models requires a vast amount of input data from local conditions to building characteristics. Based on Sailor's model, a web based calculator has been developed to quantify energy savings, but it is only available for U.S. cities. (Green Building Research Laboratory Websites, 2016). Here, we demonstrate the effects of added insulation of green roofs to reduce the heating load with a model suggested by a senior researcher in energy technology (personal communication, Jokisalo, 2012): We calculate the hourly heat losses of the green roof and the reference roof, and compare the differences between them. Hourly heat losses (q) are calculated as in equation (3), where $U =$ Coefficient of thermal transmittance, A $=$ Roof area, $T_s =$ Target temperature °C inside the building, $T_u =$ Hourly average temperature °C outside (Seppänen, 2001).

$$q = U_1 \times A \times (T_s - T_u). \tag{3}$$

Next, by taking the average of the difference in the annual heat losses of the chosen reference years, we get an estimate for the impact of the green roof on the annual heat loss of a building. To get the impact of the green roof on the energy consumption, we still need to divide the reduction in the heat loss by the combined efficiency of the heat supply and heat delivery system of the building, for example, 95% for a building with a radiator and 100% for an electric heating system (FEA, 2012). Finally, we get the annual savings on the energy use (kWh), converted into monetary savings by multiplication with the price of energy for those buildings heated by district heating (80% share) and with the price of electricity for those building heated by electricity (20% share). The average price of electricity per kWh in Helsinki is 0.115€ and the price of energy used for district heating is around 0.081€ (Energy Authority, 2016). The average price per kWh is then around 0.9€/kWh. Around 30% of the price (of both) are taxes (around 0.27€ per kWh).

We use the same price for both the private and the social benefits, albeit for different reasons. For private benefits, the taxes are included as costs for the private decision maker. On the other hand, external costs of energy production need to be accounted for in the social case. The district heat is produced for over 90% in fossil fuel power stations (∼40% coal; ∼50 natural gas). The origin of the supplied electricity is 50% nuclear, 33% natural gas and the remainder is renewables (mainly biomass as supplementary fuel). Finland takes part in the EU Emission Trade System (ETS), which affects both the production of district heat and electricity (for units beyond a minimum size). The so-called pass through of the ETS prices into power prices is high in Finland (Honkatukia, Mälkönen & Perrels, 2008), meaning that 50%–100% of the carbon price is captured in the end use price (with a higher percentage mostly during winter months). A similarly high pass through may be assumed for district heat, which is a regulated monopoly. This means that the external costs of carbon with respect to global warming are to a large extent captured in the energy price. Now the effects of NOx and SO2 remain to be included. The co-generation power stations are fitted with sulphur and nitrogen emission reduction technology, greatly reducing the emissions of these agents. The costs of these technologies are internalized in the energy prices. Nevertheless some emissions remain of which the costs may be in the order of magnitude 0.25 eurocent/kWh (EU eXterne study, 2005). The indicative external cost per kWh of nuclear power in the EU eXterné study is also rated at approximately 0.25 eurocent/kWh.

In Helsinki, we selected one year (2008) that was near to normal with respect to the observed climate, and one that was unusually warm (2010) to account for the warming of the climate and to be more conservative when estimating the benefits. For a new building ($U = 0.09$ for the reference roof, $U = 0.08$ for the green roof) we get a total discounted benefit of $2.9€/\mathrm{m}^2$. For an older building the benefit is much higher based on the poorer insulation properties of the roof (e.g., Berardi et al., 2014).

Simulations with the heat loss model show that an increase in the average temperature (Helsinki average temperatures: summer 16.2 °C, winter −3.5 °C (FMI, 2015)) by 1 degree reduces the difference in the heat losses between the green roof and the reference roof around 7% compared to the initial level in Helsinki. This corresponds to around 0.1 $\mathrm{kwh}/\mathrm{m}^2$ with thermal coefficient of heat loss $U = 0.09$ for the reference roof. The same trend continues when the average temperature is increased further.

The other determining factor on the heating energy savings is the energy insulation quality of the considered building stock, and more specifically the insulation properties of the roof. Each 0.01 increase in the coefficient of heat loss of the reference roof will increase the benefit by 100% compared to the original benefit when $U = 0.09$, assuming that with a green roof $U = 0.08$ is achieved. Decrease in the thermal transmittance can be achieved by green roof design, as demonstrated in Roche and Berardi (2014). Consequently, the effect of the building regulation has much more relative weight compared to the changes in the outside temperature. The heating energy savings do not need to drastically decrease when moving south from Helsinki if the building code is less strict in relation to the insulation properties of the roof. As an example, for Madrid in Spain, with average winter temperature of 9.7 °C (Saiz, Kennedy, Bass & Presnail, 2006) and heat loss coefficient U of 0.15, the benefit would translate into around 1.5€/m^2. However, the optimal design of a green roof in Spain would have less insulation to maximize the cooling benefits, as additional insulation could in fact increase the energy consumption by overheating the building. (Roche & Berardi, 2014). Consequently, in reality the heating savings in a warm climate are close to zero.

3.2.2 Energy cost savings for cooling

The cooling savings are estimated using results from the cooling energy simulations by Saiz et al. (2006) and Roche and Berardi (2014). Saiz et al. (2006) obtained results from an eight-story residential building located in Madrid (average temperatures, summer 19.4 °C, winter 9.7 °C) with a flat roof and total living area of 3381 m^2 and annual cooling energy use around 90,000 kWh or 27 kWh/m^2. The green roof was found to have a cooling impact on the five highest floors with a total effect of around 10% on these floors. For the highest floor or for a one-floor building, the cooling energy was reduced by around 25%. The green roof was a standard extensive green roof, with 9 cm substrate and plant types of sedum, cactus desert shrub. Roche and Berardi (2014) compared different types of green roofs in three different climate conditions for a one-story office building, and recorded annual cooling load reductions between 17% and 22% for optimal green roof designs in different climates.

In Finland, much more energy is used for heating buildings than for cooling them. Simulations show that a reference model building in southern Finland consumes around 3 kWh/m^2 per year for cooling in the current climate with a small expected increase in the future to at most 3.5 kWh/m^2 in 2030 (Jylhä et al., 2012). The benefit would then translate to 1.5–2.2€/floor m^2 (buildings are cooled with electricity) which in a building with one floor is roughly the same for the roof area for a flat roof. An example office building in Jylhä et al. (2012) uses relatively more energy for cooling than a residential building. The energy demand for cooling in southern Finland was estimated to be 7 kWh/m^2 per year at 2010 and 7.5 kWh/m^2 in 2030. For such a building, the reduction in the energy demand for cooling is then roughly 10%. The benefit is then 2€/floor m^2. For an office building with five floors, this roughly equates to 10€/m^2 per installed green roof. This is close to the maximum benefit as addition of more stores to the building does not increase the benefit since the marginal benefit per store is decreasing and approaches zero at the sixth highest floor.

For comparison in Madrid, the eight-story residential building would have a total discounted benefit of around 24€/m^2. As the benefit is calculated for a residential building, the benefit would be even larger for a commercial building that tends to use more energy for cooling.

It must be noted that these benefits are likely for green roof designs optimized for cooling the building and the maximum benefits of heating and cooling are hard to realize at the same time. Roche and Berardi (2014) proposed "active green roofs" to partly solve this dilemma, in which the cooling in the summer is increased with a plenum fan and variable insulation can be achieved.

3.3 Noise insulation

Lightweight vegetated roofs may increase transmission loss up to 10 dB at low frequency and up to 20 dB at mid-range frequencies (Connelly & Hodgson, 2013). Connelly and Hodgson (2013) show that the noise insulation benefits of green roofs are comparable or better to an additional, though unspecified, ceiling element. We use the cost of adding a plasterboard layer, a widely used technique to improve the noise insulation (personal communication, Helimäki, 2013), on a roof as the maximum sound insulation benefit of a green roof. We estimate that the benefit of a green roof is this avoided cost under flight routes. In other areas we assume that the benefit is zero, even though large amounts of green roofs in downtown areas may also affect the soundscape of the inner city, generally in the sense of attenuating mechanical noises (Irvine et al., 2009; Renterghem, Hornikx, Forssen & Botteldooren, 2013).

The total costs of plasterboard installation are around 20€/m^2 in Finland, of which around 50% is attributable to labor costs (net costs 50€/h) (prices for materials and contracts e.g., Gyproc, 2015; Kodinremontit.fi, 2015).

3.4 Storm-water management

Green roofs can reduce the demand on sewer system capacity by delaying water flows and reducing total runoff by retaining part of the rainfall and releasing it back to the atmosphere by evapotranspiration. Results from Berlin suggest that a light ($<$100 mm substrate) low-growth green roof on 10% of the building stock would result in a reduction of 2.7% in runoff for the region and 54% for the individual buildings (Mentens, Raes & Hermy, 2006). Rosenzweig et al. (2006) showed that a similar green roof infrastructure in New York could produce a 2% reduction in total runoff.

In Helsinki, the storm-water management can be divided into two main categories: combined storm-water–sewer systems and separated systems. In the combined systems both the storm water and sanitation waters are conveyed through the same pipes to the water treatment facility. In a separated system the different types of water are conveyed through separate courses. In the downtown area of Helsinki ($\sim$2200 hectares) the storm-water and sewer system is combined; in other parts of Helsinki mainly separate systems are in use. Of the over 1900 km of sewer pipes about 250 km are built as combined sewer system and 1650 km as separate system. The expansion of the sewer network (almost all new sewers are separate systems) incurs annual costs of 4 million € for the storm water alone. The repair of the existing storm-water pipes costs around 2 million € per year. The repair costs of combined systems are around 5–10 million € per year, of which 2–4 million € is allocated to storm-water-induced repair costs (personal communication Heinonen, 2012). The discounted total costs of rain water purification are shown in Table 1.

In the future, repair costs are estimated to rise to double or triple the current level, as a consequence of (over)aging of the sewer systems. The annual expansion costs of the network are expected to rise about 20%, since the new pipes should have larger sizes to account for the effects of climate change. In several cost-benefit analyses it has been assumed that there is a linear relationship between the amount of reduced runoff and the reduction in the capital and purification expenditures (e.g., Rosenzweig et al., 2006). However, based on our interview (personal communication Heinonen, 2012), some costs are fixed even in the long term and the amount of runoff has only a small effect on these costs.

Three kinds of capital expenditure are taken into account in our analysis: (1) the building of new (separate) sewer systems, (2) the repair of existing separate sewer infrastructure and (3) the repair of existing combined sewer system. We assume that at a 10% infrastructure scenario (10% of roof space is greened in Helsinki and uniformly distributed across the inner city), the resizing costs of the pipes would go down 10% (personal communication Heinonen, 2012). As for the other cost

Table 1 Expenditure categories and estimated avoided costs.

Cost type	Total discounted costs (million €)	Costs related to resizing of the pipes (million €)	Estimates for the avoided costs of 10 pct. infrastructure scenario (million €)
Rain water purification	26		0.5
Expansion of sewer network	100	10	1–4
Repair of separate sewer infrastructure	110	30	3–6.3
Repair of combined sewer infrastructure	110	23	2.3–5.6

reductions, we can also speculate that a 10% green roof scenario would reduce other costs by 2%–3% with the usual assumption of a linear runoff reduction–cost-reduction relationship (e.g., in Rosenzweig et al., 2006).

Our cost-reduction estimates based on the 10% infrastructure scenario are shown in Table 1.

These assumptions would result into benefits between 6.8 and 16.4 million € . The range of the green roof benefit for storm-water reduction is then 3.9€–9.4€/m^2. It must be noted that compared to some earlier estimates (e.g., Bianchini and Hewage, 39$–100$/m^2), these figures are on relatively low level. The realization of the higher figures would mean that savings around 20%–30% should be achieved with 10% green roof infrastructure scenario. This does not seem plausible based on the literature or the interview (personal communication, Heinonen, 2012).

Out of the different cost types in Table 1, only the annual water purification costs are directly related to the amount of precipitation and only in those areas where combined sewer system is used. The annual average precipitation is around 7000 mm in Helsinki (FMI, 2015).

The capital expenditure benefits are affected by more complicated relationships between rainfall patterns (e.g., return periods of extreme rainfall events) and city-specific storm-water and sewage system infrastructure. An important factor is the current state of the sewer infrastructure: the capacity is usually designed for a return period of a certain extreme rainfall event. In the future, sewer systems in many parts of the world will be under ever more stress due to expected increase in extreme rain events due to climate change (e.g., IPCC, 2014).

The storm-water benefit is then positively dependent on (1) the amount of precipitation (2) backlog of the current sewer system, the more outdated the system, the larger the benefit (3) occurrence and intensity of extreme rain events and (4) expected changes in extreme rainfall events due to climate change. All these need to be evaluated separately in each site. As mentioned, the figures in Helsinki are relatively low compared to other estimates, and the benefits are likely to be much higher in other cities.

3.5 Air-quality improvements

Tan and Sia (2005) found that the levels of fine particles (PM_x) and sulphur dioxide (SO_2) decreased by 6% and 37% in the immediate surrounding air space after a green roof was installed. Currie and Bass (2008) estimated that 109 ha of green roofs in Toronto could remove about 8 tons of unspecified air pollutants per year. Peck (2003) estimated that current roof greening in Toronto (cover over 6.5 million m^2) results in a 5–10% reduction in nitrogen dioxide (NO_2) and SO_2, and in a reduction of 30 tons of PM_x. Yang, Yu and Gong (2008) showed that a total of 1675 kg of air pollutants was removed by 19.8 ha of green roofs in one year in Chicago with the following distribution: 52% of ozone (0_3), 27% of NO_2, 14% of PM_{10} and 7% of SO_2. The annual total removal per ha of green roof was then 85 kg, of which 44 kg of 0_3, 23 kg of NO_2, 12 kg of PM_{10} and 6 kg of SO_2. Yang et al. (2008) reported that their estimate was 18% higher compared to above cited estimates from Toronto (Currie & Bass, 2008). In this article, we utilize proportions of gas reductions from Yang et al. (2008) and use their estimate of total removal as our high estimate and the result from Toronto (Currie & Bass, 2008) as our low estimate for green roof air purification potential.

The average costs of different emissions were studied in a report by the Finnish Transport Agency (Tervonen & Ristikartano, 2010). The calculations include negative effects on health (e.g., cancer, heart and lung diseases), environment, infrastructure (e.g., corrosion) and climate change (of GHGs). The costs were significantly higher in urban areas since there pollutants have an effect on a higher number of people. Their valuation is based on methods dealing with valuing reduced mortality risks and valuing reduced morbidity risks (Freeman et al., 2014). The results of the air-quality benefits are shown in Table 2. Summing up the effects regarding each agent in Table 2, the total air-quality benefit in Helsinki is between 4.8€ and 6.9€/m^2.

Results show, that at least 95% of the air-quality benefits can be attributed to the removal of particulate matter. Consequently, the air-quality benefit is positively dependent on the uptake potential of green roofs for PM_x and the (local) marginal cost of the PM_x. The exact concentration-response function for PM_x

Table 2 Green roof emission reduction benefits.

Type of emission	Uptake (kg $ha^{-1}yr^{-1}$)	Benefit (€ $ha^{-1}yr^{-1}$)	NPV Benefit/m^2 (€)
O_3	30–44	not quantified	not quantified
NO_x	16–23	20–30	**0.05–0.07**
PM_x	8–12	1920–2780	**4.57–6.62**
SO_2	4–6	60–90	**0.15–0.21**

is unknown, but based on current evidence, the marginal social cost of PM_x is increasing with the concentration (Beelen et al., 2015; Wyzga & Rohr, 2015). Consequently, air-quality benefits are expected to be higher in those sites with higher concentration of particulate matter compared to Helsinki. Compared to most cities across Europe, Helsinki ranks as one of the lowest for concentrations of particulate matter (visualization and statistics available at EEA website, 2015). As the concentration-response function is unknown, local estimates of marginal costs need to be employed to give more accurate results. In Helsinki, a marginal social cost of 232 800€ for a ton of particulate matter was used (Tervonen & Ristikartano, 2010). The benefits of air-quality improvements are prone to changes in the transport fuel mix. The pace of change is however too speculative to take into account.

3.6 Heat-island effect

In urban environments, vegetation has largely been replaced by impervious and often dark surfaces. These conditions contribute to the urban heat-island effect, wherein urban regions are significantly warmer than the surrounding suburban and rural areas, especially in the nighttime. One of the benefits of green roofs is mitigation of the urban heat-island effect (Berardi et al., 2014). A study by Santamouris (2014) reviewed urban heat-island mitigation techniques, and remarked that large-scale application of green roofs could reduce the ambient temperature by 0.3 K to 3 K.

The value of the benefits and costs of the heat-island effect in Helsinki or other cities in cold climates has not been estimated or even comprehensively qualitatively listed. Some impacts are positive (such as reduced energy demand in the winter) and some negative (increased mortality during heat waves is shown by Ruuhela, Lahtinen, Haga, Fronzek and Carter (2012)). The value of the urban heat-island benefit/cost is not included in the cost-benefit calculation of Helsinki.

By only considering the price of saved cooling energy, Bianchini and Hewage (2012) considered that extensive green roofs could generate a benefit of 1.2\$–3\$ and Rosenzweig et al. (2006) that the energy savings of the cooling costs could be in the range of 0.7–10%. As the difference between the low and high estimates is high, and only the decrease in energy consumption has been taken into account, it can be noted that the monetary benefit of green roofs for urban heat-island mitigation is still largely unknown.

4 Valuation of scenic benefits

All of the reviewed articles of green roof economics stated that green roofs offer amenity, aesthetic, psychological or other cultural benefits to urban residents. Nevertheless all but two left these benefits out of the cost-benefit calculations. The first exception was a study in New York (Rosenzweig et al., 2006) in which it was assumed that between 0.9 and 3.4 million residents of New York City would enjoy having half of city's roofs greened, with each resident willing to pay \$10, \$25 or \$50 for the installation. These estimates were not supported by any valuation study. The second exception was the study by Bianchini and Hewage (2012) in which it was assumed that "the aesthetics benefit obtained from extensive green roofs varies from 2% to 5% of property value. For intensive green roofs the aesthetics benefit is considered that varies from 5% to 8% of the property." These numbers were based solely on assumptions. A review article on green roof economic benefits by the U.S. Government (2011) stated that: "... studies are not specifically related to green roofs and the methodology is open to debate; productivity, absenteeism, aesthetics, and views were not accounted for in the cost-benefit analysis (CBA). The overall evidence, however, is that green roofs have the capacity to provide significant value in terms of productivity and absenteeism to the tenants (and thus the owner) as well as to the community at large who benefit from the improved aesthetics and views of the green roof."

4.1 The study method and discussion of the proxy

White and Gatersleben (2011) compared the aesthetic quality of different roof types and found that people prefer view to a nonvegetated roof. Fernandez-Cañero, Emilsson, Fernandez-Barba and Machuca (2013) argue that green roofs with similar appearances to conventional green areas are most valued by citizens and the closer their design is to that of conventional urban green, the more comparable the aesthetic quality is to conventional urban green. Jungels, Rakow, Allred and Skelly (2013) showed that positive attitudes toward green roofs increased as the green roofs became more familiar. Lee, William, Sargent, Farrell and Williams (2014) confirm that green roofs carry aesthetic quality over concrete surfaces; aesthetic quality is however strongly dependent on green roof characteristics, such as choice of vegetation and diversity. Lee et al. (2015) confirm in a later study that green roofs have restorative effects comparable to conventional urban green – a view to a green roof can restore attention in the same way as a view to conventional urban green. Based on the literature, the scenic quality of green roofs may be lower than that of conventional urban green, but with good design the scenic quality approaches that of small pockets of conventional urban green. Consequently, we use the scenic value of small urban areas with green cover (referred as "small parks" from here) as the high estimate and zero as the low estimate for the scenic value of green roofs. Even though this is quite a wide range, it will define the limits based on which the scenic value can be added to the CBA.

Next, we need to (1) find the value that inhabitants place on small parks (2) isolate the scenic value from other values of urban green, for example, recreational values. To this end, we use evidence from housing transactions in Helsinki and analyze the values that individuals have placed on different proximities to different types of parks and, based on this evidence, we infer the effects of increasing urban green in Helsinki. For robustness, we also repeated the analysis in another city in Finland (Table 4c)

A spatial hedonic specification was estimated on a sample of approximately 6500 apartment transactions that took place in Helsinki's city center between 2008 and 2011. The observed dependent variable in this context is the purchase price/m^2 of the property, which can be interpreted as the present value of the stream of expected rental values; rental price is a function of a vector of amenities, of which the view to urban green is one component (Freeman et al., 2014). In our analysis, we define the scenic value to be the value that residents in the immediate vicinity (defined below) of urban green receive compared to those farther from it.

Previous work on the dataset showed that the value of urban green is highest in the city center and diminishes rapidly when moving away. For this reason, we focused on Helsinki's center in which there is the greatest potential for incremental value. We defined the point of highest density of commercial establishments as Helsinki's central business district (CBD) and then selected property transactions within 3 km from the CBD.

Urban parks are the predominant type of urban green in the study area; for Helsinki, the term refers to areas with a mix of trees, other vegetation, and artificial configurations like walkways and playgrounds. We split parks into two categories

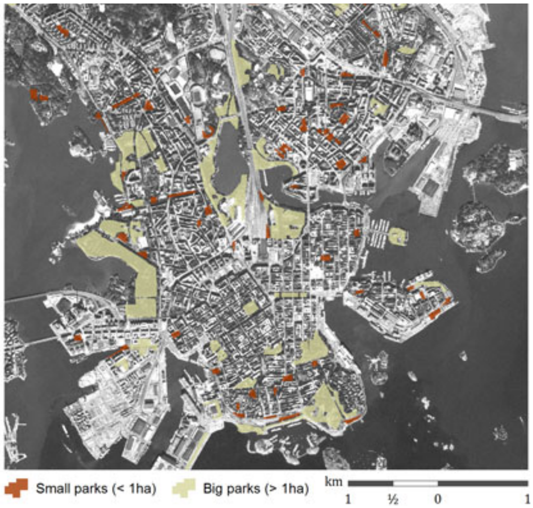

Figure 1 Helsinki's CBD and park categories.

("big parks" larger than 1 ha and "small parks" 1 ha or smaller), since we wanted to find out whether even small areas devoted to urban green can have positive effects on the housing market. Dummy variables were created for properties that are within 30, 50, and 70 meters from big and small parks. These alternative distances to a park were tested to see how varying the distance to a park affects the average WTP. Figure 1 displays the study area and park categories. The variables connected to each transaction are listed in Table 3.

For this estimation, we have used a spatial error regression specification:

$$y_i = a + \sum_{k=1}^{n} \beta S_{ki} + \sum_{j=1}^{n} \gamma N_{ji} + \sum_{l=1}^{n} \gamma E_{li} + \lambda W u_i + e_i. \tag{4}$$

In equation (4), W is a spatial weights matrix (in this case produced by a 1st order Moore neighborhood rule), Wu a spatially autocorrelated error term, e a random error term, α the intercept, and β, λ coefficients. The beta coefficients are interpreted as in nonspatial OLS regressions. The spatial error term lambda (λ) is treated in this analysis as an uninterpretable instrument that clears residuals from spatial autocorrelation. Equation (4) includes structural, neighborhood, and environmental attributes of housing (Dubin, 1992): $\boldsymbol{S}$ is a vector of k structural attributes of a property, $\boldsymbol{N}$ is a vector of j attributes describing the neighborhood of the property, and $\boldsymbol{E}$ is a vector of l attributes describing aspects of the natural environment in

Table 3 The variables of the analysis and their mean values in Helsinki's CBD.

Variable	Description	Unit	Mean
PRICE	Selling price per m^2, 2011 prices	€ thousand per m^2	4.7
DEBT	Debt component[(a)], 2011 prices	€ thousand per m^2	.18
MAINT	Monthly maintenance cost, 2011 prices	€ per m^2	3.36
ROOMS	Rooms, excluding kitchen	Multinomial (1–9 rooms)	1.96
FLOOR	The floor on which the apartment is situated	Multinomial (1^{st}–9^{th} floor)	3.53
ELEVATOR	Elevator available in the apartment block	Dummy (1: yes, 0: otherwise)	.77
AGE	Dif. between selling and construction year	Years	70.83
BADCND	Bad condition	Dummy (1: bad, 0: otherwise)	.058
AVGCND	Average condition	Dummy (1: avg., 0: otherwise)	.33
CBD	Proximity to the central business district	Meters	1692
SEAVIEW	Within 100 m from the coastline	Dummy (1: within, 0: otherwise)	.038
PARK	Within 30/50/70 m from any park	Dummy (1: within, 0: otherwise)	.21[(b)]
SMPARK	Within 30/50/70 m from a small park (<1 ha)	Dummy (1: within, 0: otherwise)	.14[(b)]
BGPARK	Within 30/50/70 m from a big park (>1 ha)	Dummy (1: within, 0: otherwise)	.067[(b)]
YEAR	Transaction year	Multinomial (2008–2011)	2010

[(a)] Refers to loans undertaken by the housing committee for large maintenance tasks (e.g., roof, pipes or structural renovations), distributed to each property usually according to its size.
[(a)] Figures for the "within 30 m" category.

the vicinity of the property. Vector E contains the target variables of this analysis (direct view to small and big parks). Equation (4) was estimated on the previously described sample and variables of Table 3. Pre- and post-estimation tests verified the assumption of spatially autocorrelated residuals and indicated that the spatial error model of equation (4) as the preferred specification as compared to a nonspatial OLS regression or alternative spatial specifications.

4.2 Estimation results and interpretation

First, we estimated the value of any urban park, regardless of its size, within 30, 50 and 70 m of a building (Table 4a). The value of a presence of urban green is significant in all of the tested distances. The average marginal value is highest for buildings within the 30 m radius from a park and decreases when increasing the allowed distance from the park. The average values for the respective distances are 134€, 122€ and 94€ per m^2 of living space. It has been empirically shown (Crompton, 2001) that the incremental of value attributable to the park significantly

Table 4a–c Hedonic regression results for the CBDs of Helsinki and Pori (dependent variable: Price/m^2 in € thousand, 2011 prices)

	Coefficient *(std. error and significance)*								
	(4a) Helsinki, any park			**(4b) Helsinki, small and big parks separately**			**(4c) Pori, small and big parks separately**		
	30 m	**50 m**	**70 m**	**30 m**	**50 m**	**70 m**	**30 m**	**50 m**	**70 m**
INTERCEPT	−479.322	−482.076	−481.22	−479.895	−482.31	−481.156	−128.042	−128.287	−126.852
	*(15.806***)*	*(15.797***)*	*(15.768***)*	*(15.807***)*	*(15.793***)*	*(15.77***)*	*(16.086***)*	*(16.0781***)*	*(16.0523***)*
DEBT	−.384	−.384	−.374	−.384	−.385	−.375	−.811	−.81	−.817
	*(.022***)*	*(.0222***)*	*(.0225***)*	*(.022***)*	*(.0222***)*	*(.0225***)*	*(.017***)*	*(.0167***)*	*(.0167***)*
MAINT	−.00959	−.0101	−.00879	−.0105	−.011	−.00921	.0263	.025	.028
	(.00934)	*(.00932)*	*(.00932)*	*(.00935)*	*(.00932)*	*(.00931)*	*(.0123*)*	*(.0124*)*	*(.0122*)*
ROOMS	−.193	−.195	−.199	−.193	−.196	−.199	−.0911	−.0911	−.0932
	*(.0095***)*	*(.0095***)*	*(.00951***)*	*(.0095***)*	*(.0095***)*	*(.00951***)*	*(.00919***)*	*(.0092***)*	*(.00917***)*
ELEVATOR	.0345	.0309	.0293	.0345	.0314	.0301	.0213	.0223	.0295
	(.0279)	*(.0278)*	*(.0279)*	*(.0279)*	*(.0278)*	*(.0279)*	*(.0205)*	*(.0203)*	*(.02)*
AGE	−.0187	−.0188	−.0189	−.0188	−.019	−.0189	−.0322	−.0324	−.0326
	*(.00191***)*	*(.0019***)*	*(.0019***)*	*(.00191***)*	*(.0019***)*	*(.0019***)*	*(.00105***)*	*(.00105***)*	*(.00104***)*
[AGE]^2	.000164	.000164	.000163	.000164	.000165	.000164	.000202	.000203	.000205
	*(.0000148***)*	*(.0000147***)*	*(.0000147***)*	*(.0000148***)*	*(.0000147***)*	*(.0000147***)*	*(.00000847***)*	*(.00000845***)*	*(.00000838***)*
FLOOR	.0858	.086	.0851	.0858	.0862	.0853	.0256	.0252	.0259
	*(.00473***)*	*(.00473***)*	*(.00472***)*	*(.00473***)*	*(.00472***)*	*(.00472***)*	*(.00475***)*	*(.00473***)*	*(.00472***)*
BADCOND	−.669	−.668	−.674	−.67	−.668	−.673	−.418	−.416	−.416
	*(.0357***)*	*(.0357***)*	*(.0356***)*	*(.0357***)*	*(.0357***)*	*(.0356***)*	*(.0534***)*	*(.0534***)*	*(.0534***)*

Continued on next page.

Table 4a–c (Continued).

AVGCOND	−.323	−.323	−.326	−.323	−.323	−.326	−.197	−.196	−.198
	*(.018***)*	*(.018***)*	*(.018***)*	*(.018***)*	*(.018***)*	*(.018***)*	*(.0218***)*	*(.0218***)*	*(.0218***)*
log [CBD]	−.911	−.915	−.914	−.909	−.903	−.905			
	*(.0432***)*	*(.043***)*	*(.0429***)*	*(.0431***)*	*(.043***)*	*(.0429***)*			
SEAVIEW	.447	.455	.462	.438	.436	.453			
	*(.0872***)*	*(.0869***)*	*(.0868***)*	*(.0874***)*	*(.087***)*	*(.0866***)*			
RIVERVIEW							.0319	.0304	.0286
							(.0651)	*(.0649)*	*(.0641)*
PARK	.134	.122	.094	.134					
	*(.043**)*	*(.0394**)*	*(.0371*)*						
SMPARK				.132	.05	.0583	.0311	.00147	.054
				(.0518)*	*(.0477)*	*(.0433)*	*(.0305)*	*(.0274)*	*(.0232*)*
BGPARK				.203	.249	.183	.0653	.0791	.0773
				*(.0682**)*	*(.0612***)*	*(.055***)*	*(.0268*)*	*(.025**)*	*(.0237**)*
YEAR	.245	.246	.245	.245	.246	.245	.0651	.0652	.0645
	*(.00787***)*	*(.00787***)*	*(.00785***)*	*(.00787***)*	*(.00787***)*	*(.00785***)*	*(.00801***)*	*(.008***)*	*(.00799***)*
Number of obs.	6882	6879	6859	6882	6879	6859	1361	1361	1361
Pseudo-R^2	.554	.554	.555	.554	.555	.555	.756	.756	.757
AIC (OLS AIC)	14967 (17208)	14943 (17176)	14853 (17057)	14963 (17171)	14932 (17129)	14850 (17018)	604 (675)	602 (672)	595 (660)

Significance ranges: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1.

increases with the size of the park; for instance, in an early study by Coughlin and Kawasima (1973) it was found that a 5-acre park (2 ha) had almost five times the increase in the price of a dwelling unit than a 1-acre park (0.4 ha) and it was also found that the incremental value attributable to a small park decreased more quickly as the distance to the park increased. Our findings were similar regarding the effects of park size (Table 4b). The value of a big park for buildings within 30 m from the park was in average 200€ per square meter while the value of a small park was 130€. However, when increasing the distance radius including also buildings within 50 m from the parks, the average value of a big park was almost 250€ while the average value of a small park was around 50€. We interpret that this shows that the recreational value of a big park is still available when allowing a longer distance, but the presence of a small park bears mainly scenic value that goes down quickly as the view gets blocked.

Based on GIS analysis, small parks are mainly visible to those building within 30 m radius, and the view is more or less blocked when increasing the radius. However, all of the services related to recreational or other use values of the parks are still present and (almost) as easily available at the radius between 30 and 50 m from the small parks. Consequently, we take the value that is attached to small parks at 30–50 m radius and deduct that from the total value of the parks available between 0 and 30 m radii. We define the residual as the "scenic value" of small parks. This is around 110€ per square meter as the value of a small park decreases fast when increasing the distance as expected from the literature, and the mean value attached to a small patch of urban green is only around 20€ per square meter at the distance between 30 and 50 m from the park.

In percentage terms, the range for the scenic benefit of the green roofs is 0–2.3% without taking the vertical location of the green roof into account. However, this undermines the fact that compared to a park, the view to a green roof is limited, as only those neighbors that live on a higher floor compared to the green roof, are able to actually enjoy the view. Consequently, the building heights distribution needs to be taken into account. As in figure 2, around 37% of the buildings in the study area are buildings with 1–2 floors, and 63% of the buildings have three or more floors. If all the green roofs are installed on the buildings with either one or two floors, we assume that out of the buildings with 1–2 floors 25% of the residents live on a higher level than the green roofs, and 66% of the residents on a 3+ building live on a higher level than the green roofs. In total, the vertical location of the green roof would limit the view from 46% of those apartments that would have had a view to an urban park. To take this into account, the high estimate for the value of having a green roof within 30 m from the building drops to 1.2%.

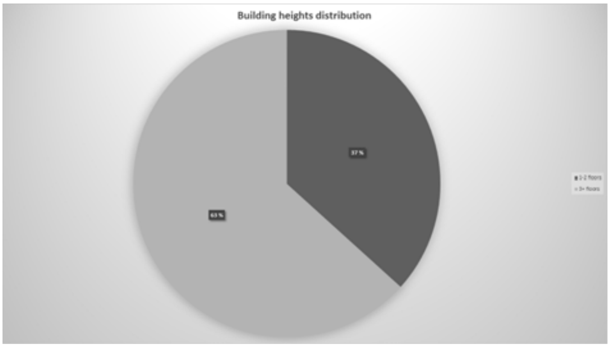

Figure 2 The distribution of building heights in Helsinki, Finland.

The only comparison in the literature is Bianchini and Hewage (2012) in which the value of properties was assumed to be 2%–5% higher for extensive green roofs. Based on our results, we recommend to use value increases between 0% and 1.2% for those properties in the immediate vicinity (within 30 m) of a green roof.

4.3 Simulation of the scenic value in Helsinki

We analyze two scenarios (Figure 2): (1) high benefit simulation (Simulation 1) in which all the roofs that are greened are placed in the CBD, which would result in 50% of roofs in the CBD being green and would yield the highest pay-off and (2) low benefit simulation (Simulation (2) with equal distribution of green roofs across the broader urban area of Helsinki in which 10% of the CBD roof tops are greened. In both of the cases we assume that (i) the average marginal value of increase in urban green drops linearly to zero once the last simulated green roof has been installed, and (ii) the average marginal value of the scenic value of a green roof is between 0% and 1.2% as explained above.

We start by surveying the current green cover in Helsinki and adding green space to those areas with the least green space. Before the simulation (1) 26% or 629 buildings out of 2415 in our delineation of Helsinki's CDB were situated within 50 m from a big park or within 30 m from a small park. The total amount of roof area in the city of Helsinki is around 1740 ha, approximately 19% of 334 ha of which is located in the study area (CBD). In simulation 1, 174 ha green roofs would all be located in the CBD. We simulated this additional green cover by placing green roofs in a GIS software in those areas that currently exhibit the

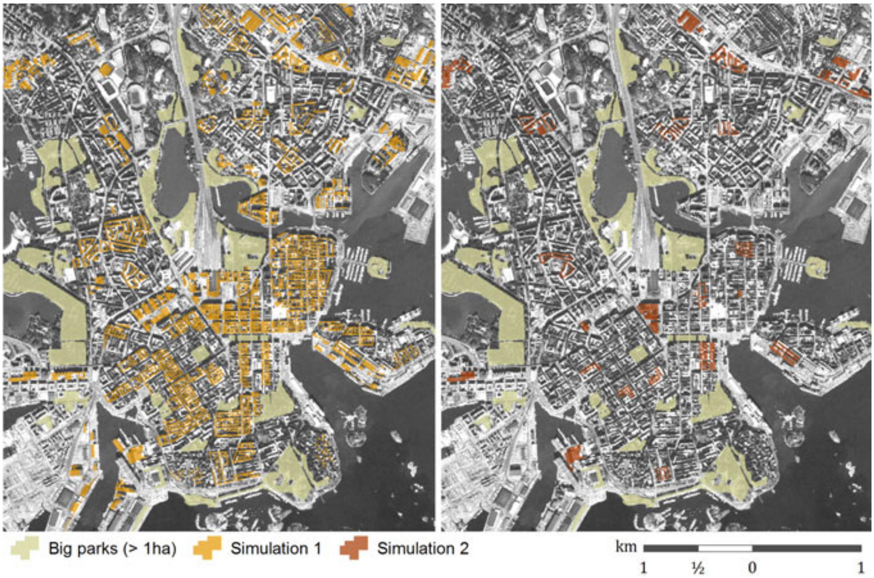

Figure 3 The simulations (1) and (2) of green roof cover in Helsinki CBD.

highest distances to urban parks. We selected adjacent rooftops that would generate large green cover areas. Our selection for simulation (1) is shown in figure 3 on the left hand side. After the simulation, 68% of the buildings or 1652 of the buildings in the CBD had a presence of either a green roof or a small park within 30 meters, or a big park within 50 meters. The residential living area in the CBD is around 550 ha. (Helsinki Statistics). With assumptions (i) and (ii), the benefit of a green roof would be between 0 and 37€/m^2. The 37€/m^2 can be seen as the upper limit for the value of the scenic benefit of green roofs in Helsinki as it relies on the assumptions that (1) green roofs are optimally placed in those areas with the least amount of urban green and highest property values, (2) green roofs carry the same scenic value as small urban parks and (3) they are optimally placed on the low-rise buildings.

The second simulation was done by assuming a uniform distribution of green roofs across the city of Helsinki, so that only 10% of the CDB roofs were greened. We again, simulated green roof cover by placing green roofs to those areas of CBD with the lowest proximity to urban green depicted in figure 3 on the right hand side. After the simulation, 38% of the buildings had either a green roof or a small park within 30 m, or a big park within 50 m from the building. With assumptions (i) and (ii), the value of the increase per installed green roof would be 0–17€/m^2.

This range can be regarded as more realistic, as it relies only on assumptions that (1) green roofs would carry value on those areas with the lowest amount of urban green (CBD), (2) the scenic value would be close to that of a small park without its use values, and (3) the value of the green roofs last green installed last green roofs would approach zero as the supply of urban green is less scarce.

Out of the other benefits, only the air-quality benefits can be partly included twice if the scenic benefits are fully incorporated into the CBA. If air-quality benefits are conservatively – to avoid double counting – reduced from the scenic benefits of the green roofs, the scenic benefits of green roofs are between 0 and 10€/m^2

5 Costs of green roofs

The main barrier for green roof implementation is the additional costs compared to standard roof solutions (e.g., Berardi et al., 2014; Clark et al., 2008). The cost levels for extensive green roofs exhibit significant differences across the world. The high estimate of the literature can be found in Sproul et al. (2013) in which cost level of 150€/m^2 for extensive green roofs is assumed. Almost as high figures were reported in Bianchini and Hewage (2012) in which the costs of extensive green roofs were approximated to be 90€/m^2–113€/m^2 in British Columbia, Canada. However, neither of the aforementioned studies elaborate whether the costs were additional costs compared to reference roof or total costs. Additional costs of 68€/m^2 were applied in a study by Carter et al. (2008) in City of Atlanta. In a literature review report from 2007, Toronto Region Conservation (Toronto Region Conservation (TRC), 2007) confirms the wide range of initial capital costs across the world. In North America, with very low implementation rates of green roofs across the continent, the additional costs of extensive green roofs ranged from 45€/m^2 to 190€/m^2. However, in Germany with established green roofs industry and higher implementation rates, the additional costs were only around 13€/m^2–41€/m^2.

To get an appreciation of the cost level in Finland, green roof suppliers were interviewed. Our example roofs are built on a supporting structure and the cost estimates are based on the assumption that the roof will be built on an existing building or to a new building with sufficient loading capacity. This section is an updated version of chapter 5 of a project report by Nurmi, Votsis, Perrels and Lehvävirta (2013).

- The standard bitumen roof costs are around 35€/m^2 (+VAT 24%, = 43€/m^2). This includes rubber bitumen layers, waterproofing and installation. These installations are needed also under green roofs (with some modifications, the costs remain approximately the same).

- The additional costs to install a green roof are on average around 50€/m^2 (+VAT 24 %, = 62€/m^2). The additional costs include the sedum mats (53% of the additional costs), the installation costs (around 24% of the additional costs) and taxes (23%).

The least expensive green roof is achieved by installing a drainage layer, filter fabric, substrate, and plants from cuttings and seeds. These green roofs may allow for more plant diversity if a deeper substrate is used, but require more structural capacity to hold the weight of the soil. They are generally at least 20% less expensive than ready-made green roof sedum mat systems, the total extra costs being around 40€/m^2 (+ VAT 24%).

Cost estimates from Finland are very high in comparison with estimates in those countries with established green roof industries, such as Germany. The low price level in Germany is a result of more than thirty years of market development. In Switzerland low cost solutions cost only around 20€/m^2 (personal communication Brenneisen, 2013) despite the high price level of the country. In new markets competition is scarce and no economies of scale exist, labor is more expensive since installers lack experience, and there is a tendency to use custom-design systems. Obviously, adopting low cost techniques would support the proliferation of green roofs. The additional costs of a green roof have gone down by 33%–50% (Toronto Region Conservation (TRC), 2007) since the industry has established itself. In our scenarios we assume that the same would happen in Finland if 10% of roof top area in Helsinki was greened. For comparison in Basel, of which around 30% of flat roofs or 3% of total roof area is green, the additional costs have gone down from around 80 euros to only around 15 euros per square meter (ZHAW, 2013), making our cost-reduction estimate fairly conservative.

6 Results of the cost-benefit analysis

In this section, we wrap up the estimates of benefits and costs in Helsinki, Finland. First, we discuss the private incentives to build green roofs. Next, we take a look at the public benefits assuming that 10% of Helsinki's roofs are converted to green roofs. By modifying the values of different ES based on the target cities characteristics as described in Section 4, it is then easy to see how the cost-benefit ratio would change when replacing Helsinki for another case-study location.

Table 5a Private Cost-benefit analysis, with 90%–110% sensitivity analysis.

	Low benefit, high cost scenario (€/m^2)	**High benefit, low cost scenario (€/m^2)**	**Relevant factors affecting the value**
Additional costs of installation	62	50	Lower costs possible for buildings with strong structural capacity
Private benefits:			
Energy savings for heating	2.7 (90%)	3.3(110%)	Isolative properties of the alternative roof; Green roof design
Energy savings for cooling	1.4 (90%)	11 (110%)	Use of the building, used A/C-method; Green roof design
Membrane longevity	21.4 (90%)	26.2 (110%)	Service life of a green roof vs. that of conventional roof
Sound insulation	0	20	Benefits for those in air-traffic noise zones
B/C-ratio	**0.4**	**0.8** (1.2 with sound insulation benefits)	

6.1 Private benefits versus private costs

Only a part of the aforementioned benefits accrue to the owner of the property where the green roof is installed, however all the costs are levied on the private decision maker (Table 5a). A higher price of the roof also increases the value-added tax burden on the investor. The private benefits and costs also include avoided and incurred tax costs (namely VAT) for the property owner.

In Table 5a we list the private costs and benefits. All of these benefits are of the same nature – they are avoided costs for the property owner and represent the WTP. These kinds of benefits can be summed together (as shown in Section 2) and are the same for any building owner. The analysis shows that the current level of costs is too high compared to the benefits for a private decision maker to have an incentive to install a green roof, the B/C-ratio is between 0.4 and 0.8 and the NPV is -36.5–-9.5€/m^2. The expected value for NPV is -257€/m^2, assuming uniform distribution for other benefits except sound insulation (0 for 98.5%; 20€/m^2 for 1.5% population under flight routes) and taking into account that both cooling and heating benefits are hard to achieve with the same design of the green roof. These results are in line with results from other cities as indicated by the literature review.

Table 5b Social Cost-benefit analysis.

	Low benefit, High cost scenario (€/m²)	**High benefit, Low cost scenario (€/m²)**	**Relevant factors**
Additional costs of installation	33.5	25	Calculated for the current standard solution – sedum mats, market structure
Private benefits	21	54	High scenario includes sound insulation benefits
Public benefits:			
Storm-water management	3.5 (90%)	10.3 (110%)	Assumptions on the reduction of storm-water infrastructure
Air-quality benefits	4.3 0%)	7.6 (110%)	The green roof performance in the climate conditions of southern Finland
Scenic benefits		11€ (110%)	Green roof design and visibility
Social B/C-ratio	**0.9**	**2.5** (3.5 with sound insulation benefits)	

We present both the lower and higher bounds for the benefits and vice versa for the costs.

6.2 Social cost-benefit analysis with 10% installation scenario in Helsinki

Next, we take a look at the social costs and benefits in a scenario in which green roofs have been installed in 10% of the building tops in Helsinki. In addition to the private ones, public benefits are expected to emerge. We assume that higher implementation rates would lower the additional costs of green roofs by at least 33% and at most 50%, as explained in Section 5. In Table 5b we list the social benefits including both private and public. Here we also exclude taxes (from the membrane longevity and sound insulation benefits) from the calculations – unlike in Table 5a – as we are interested in the social benefits instead of private incentives. The social B/C-ratio is between 0.9 and 2.1, and NPV is between -4.7 and $37.9€/m^2$ and possibly even higher on those areas with air-traffic noise. The expected value for the social NPV is $13.4€/m^2$ with the same assumptions as for the private benefits. The focus of this study – the scenic benefits – represent 13% of the total benefits in the high estimate case, or around 13% of the expected value of the benefits. Consequently, while not insignificant, the addition of the scenic benefits only strengthens the conclusion that while the private benefits are not high enough to cover the installation costs, the social CBA shows positive results.

7 Conclusions

The aim of this article was to discuss the economic benefits and costs of thin, lightweight green roofs with special emphasis on the previously unmeasured benefit of the increase in the scenic value.

The main conclusions of green roof CBA in Helsinki are:

(1) As the reviewed literature would suggest, the private benefits are usually not high enough to cover the current level of additional private costs. In Helsinki, even in the low cost-high benefit scenario the private B/C-ratio is under 1. However, in some circumstances, in warm climates the cooling energy savings can drive even the private B/C-ratio slightly over 1. The most important parameters determining the private benefits are: (1) cost of the reference roof so that higher reference roof price increases the benefits, (2) temperature profile of the location so that higher temperatures increase the benefits, (3) energy price so that higher energy price increases the benefits and (4) building code of the roof so that higher coefficient of heat loss increases the benefit.

(2) When adding up private and public benefits, the benefits would surpass the costs in most of the cases, especially if a higher implementation rate drives down the costs. The factors that have a positive effect on the public benefits, which are at a relatively low level in Helsinki, are: (1) the average annual precipitation and frequency of extreme rainfall, (2) the maintenance backlog of the current sewer system and (3) the concentration of particulate matter. As also the cost level of green roofs is high in Finland, the social B/C-ratios can be expected to be higher than those reported in this study in most other cities of similar size or larger.

(3) Scenic benefits have a potential to be a significant factor in green roof CBA; the increase in the property values in the buildings within 30 m of a green roof was assessed to be between 0% and 1.2%. Helsinki is a green city compared to many other cities, thus benefits are likely to be higher in many other cities with less vegetation cover. Compared to other benefits, scenic benefits represent 13% of the total benefits of the high estimate case for social benefits, or around 13% of the expected value of the benefits.

In this study, we were able to quantify several green roof benefits, including membrane longevity, sound insulation, energy cost savings, air-quality, storm-water management and scenic benefits. Many studies also indicate that green roofs have the potential to increase urban biodiversity, but this benefit was not in the scope of this article. The level of benefits was found to be positively correlated with outside temperature (Section 3.2), level of precipitation and frequency of extreme downpours (Section 3.4), level of urbanization, and proximity to city center (Section 4). Presumably climate change and urbanization will drive the level of benefits higher in the future.

The costs of green roof installation were gathered by supplier interviews. The additional costs of a green roof in Finland are around 50–60€/m^2 making them more than two times more expensive than the reference roof. Cost estimates were significantly higher than in countries with long traditions in green roof implementation, namely Switzerland and Germany. The cost-benefit calculations together with the reviewed literature show that private benefits are usually not high enough to justify a green roof installation for a private decision maker. It can be expected that the level of implementation stays low in most cities with comparable climatic and ambient conditions as Helsinki without corrective policy instruments. Policy instruments could include supportive policies that turn part of the public benefits into private ones (e.g., reduction in storm-water fee). In addition, research projects and demonstration projects could drive the benefits up and the costs down.

The two main limitations of this article are related to scarcity of evidence of the impacts of green roofs in different environments. First, many of the natural processes of green roofs have been studied only in a few sites, for example, we had to rely on figures of the emission uptake in Toronto and Chicago. More research is needed in local climate conditions to obtain more reliable figures. The second limitation is of the same nature: we had to estimate the upper limit of the scenic value of green roofs by indirect means by looking at the value people attach to the presence of an urban park. We assumed that the value of the presence of an urban park is comparable to that of a presence of a green roof but took into account the reduction in the visibility.

Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/bca.2016.18.

Acknowledgments: This article is based on the dissertation work of Väinö Nurmi funded by the Nessling Foundation and on the dissertation work of Athanasios Votsis funded jointly by the Finnish Academy and the Helsinki University Centre for Environment (HENVI).

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FINNISH METEOROLOGICAL INSTITUTE
CONTRIBUTIONS No. 152
ISBN 978-952-336-075-4 (paperback)
ISSN 0782-6117
Erweko 2019

ISBN 978-952-336-076-1 (pdf)
Helsinki 2019